Proceedings of:

Precision Fabrication and Replication

1999 Spring Topical Meeting

April 13-15, 1999
The Carolina Inn
Chapel Hill, North Carolina

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Preface

This book comprises the proceedings of the 1999 Spring Topical Meeting. The contributions reflect the authors' opinions and are published as presented to ASPE, without change. Their inclusion in this publication does not necessarily constitute endorsement by the ASPE, or its editorial staff.

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1999 Spring Topical Meeting

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1999 Spring Topical Meeting

Meeting Schedule

Tuesday, April 13		Wednesday, April 14	Thursday, April 15
	7:30	REGISTRATION AND CONTINENTAL BREAKFAST	
	8:30	TECHNICAL SESSION I MOLD MAKING	TECHNICAL SESSION III REPLICATION II
	12:00		
		LUNCH	
	1:30	TECHNICAL SESSION II REPLICATION I	
	4:30		
ON-SITE REGISTRATION	5:00	OPTIONAL VISIT NCSU PRECISION ENGINEERING CENTER	
	6:30		
	7:00		
	7:30	DINNER AT N.C. MUSEUM OF ART	
	9:30		

Foreword

This spring topical meeting will provide a forum for experienced and knowledgeable individuals and organizations involved in the production of precision parts for optical, mechanical and biomedical applications. The goal will be to share experiences, compare approaches and results, and discuss research and development needs within this focused technical area.

The objective of this meeting is to bring together specialists and practitioners from industry, government and academia to provide a forum for the exchange of ideas about mold fabrication, part replication, metrology and materials. The presentations will cover a broad range of technologies and highlight potential areas for future development. The meeting will emphasize discussions as much as the presentations and the participants are encouraged to identify areas needing further research.

Organizing Committee
of the 1999 Spring Topical Meeting

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Thomas A. Dow and Alex Sohn
North Carolina State University

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Irving F. Stowers, Lawrence Livermore National Laboratory
Semyon L. Zheleznyak, Spectronic Instruments, Inc.

Technical Paper Index

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Mold Making
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Session Chair: Thomas A. Dow (North Carolina State University)

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2. ***Diamond Turning of Molds for Precision Aspherical Lenses***
   E. Brinksmeier, W. R. Preuß (University of Bremen) . . . . . page 9
3. ***Patterning Submicron Features Using Broad Beam Neutral Ion Etching***
   M. Bancu, T. G. Bifano, P. Bierden (Boston University). . . . . page 15
4. ***LIGA for Mold Fabrication****
   R. Wood (MCNC)
5. ***Micro Robot with Hopping Indenter for Micro Molding***
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Session Chair: Thomas G. Bifano (Boston University)

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2. ***Replication of High Fidelity Surface Relief Structures***
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3. ***Replication of Optical Surfaces: Capabilities and Cautions***
   F. Denton (Optometrics, Inc.), and A. E. Gee (Cranfield University) . . . . . page 39
4. ***A Precision Polymer Injection Molding Process Assisted by Infrared Radiation to Upgrade Both Optical Quality and Transcribability***
   Y. Kurosaki (The University of Electro-Communications), and I. Satoh, T. Saito (Tokyo Institute of Technology) . . . . . page 46

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Session Chair: Alex Sohn (North Carolina State University)

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   M. Nakao, J. Kumaki, Y. Hatamura (The University of Tokyo) . . . . . page 64
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Conference Summary and Discussion

** Abstract not available at press time*

Technical Papers

effect, the structure surfaces are smoothed. Electrochemical polishing has been tested for small areas (about 10 mm^2); a facility for deburring larger molds is under construction.

Hot Embossing

In the hot embossing process, a mold insert is pressed under vacuum conditions into a semi-finished thermoplastic polymer heated to a temperature above its glass transition temperature. After cooling below the glass transition temperature, the mold insert is separated from the molded microstructures. This technique concentrates on the very basic principles of thermoplastic replication: The direct control of temperature and pressure. This results in a simple machine construction and easy operation.

For the replication of microstructures vacuum hot embossing is well suited for several reasons. A thin foil of thermoplastic material is placed on top of the microstructured mold insert which is heated up, so the softened material fills up the microstructures directly from the top, resulting in a small material flow and a low induced internal stress. Residual stress can be further reduced by gradual cooling of the tool. The low flow rates imply the possibility of fabricating very delicate structures, such as free-standing thin columns or narrow walls /6/.

The microstructured mold insert is mounted on a tool and can be exchanged easily. Thus, the fabrication of prototypes and small series is not dominated by the preparation time. Another advantage of hot embossing is the use of thin films. Only the required material quantity is used and there is no waste by any injection sprue or runner system. For plastic microstructures only micrograms of polymer are needed. Thus, the material costs are no main factor of the overall costs, even when using expensive high-performance materials, such as PEEK or PSU. A characteristic feature of the hot embossing process is the residual layer on which the microstructures are located. This carrier layer serves as a magazine and allows handling of the microcomponents until they are diced. Because of the low layer thickness (<100 µm) the dicing can be realized by mechanical micromachining or etching of the unstructured side.

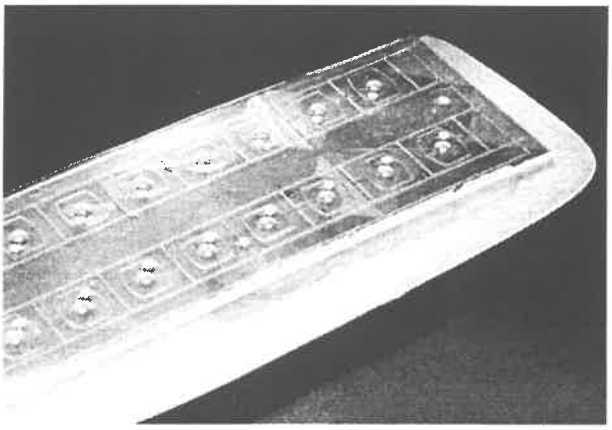

Figure 4: Batch of twelve microvalve housings, molded by hot embossing from PSU. The structure height is up to 500 µm, the thickness of the carrier layer is about 100 µm.

(Overall picture width: approx. 7 cm)

A special feature only accessible by hot embossing is the microstructuring of a polymer-coated and pre-structured substrate, e.g. ceramic or silicon wafers. By using an integrated alignment unit it is possible to position the microstructure precisely relative to the substrate. Microscopic depressions directly on top of the electronic circuits can be used for a great number of applications, e.g. for lab-on-chip devices.

Hot embossing became an important microstructuring technology, widely distributed in a lot of research laboratories. One of the first commercial applications at FZK was the small-series production of micro spectrometers. The equipment was developed in cooperation with the German company of Jenoptik Mikrotechnik and is commercially available.

Injection Molding and Related Processes

Economic success of microsystems technology demands for the cost-effective fabrication in medium and large series. Additionally, a wide range of appropriate materials as well as the related processing technologies have to be ready for industrial application. Different types of micro injection molding processes are available to meet all these requirements, but work has to be done to achieve a commercial applicability of some processes due to difficulties arising from the small dimensions of the microstructures.

Microstructures have a high surface to volume ratio. To achieve a good mold filling the tool, the micro-

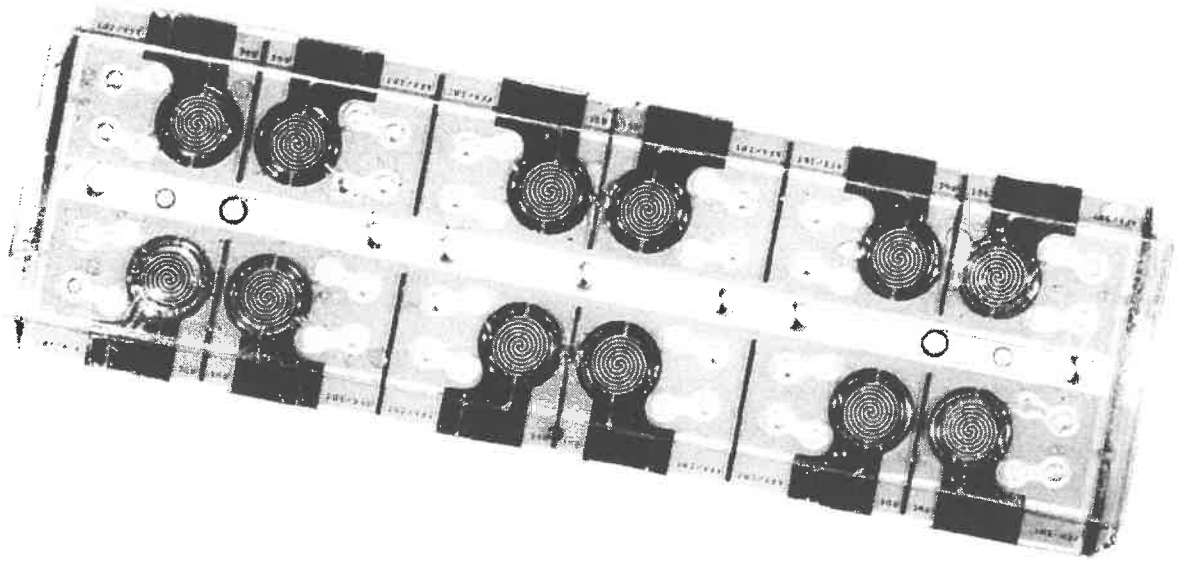

Figure 5: Array of 12 micropump housings injection-molded from PSU and assembled with a thin polymer foil supporting the thermomechanical actuators (coils) and passive valves.

(Overall feature size: 20 × 60 mm^2)

structured mold inserts have to be heated up, often above the melting temperature of the plastic material. To avoid compression of air in the tool cavities and burning of the plastic materials, the micro cavities are evacuated before injection. After form filling the tool is cooled down for demolding. The temperature cycle of the molding tool determines the cycle time of the injection molding process /7/.

An important economic factor is the optimization of the molding process and of the tools with simulation techniques. Software programs adapted from conventional injection molding can provide useful assistance for the optimization of molding tools, microstructured mold inserts and micro component design.

Presently, micro-parts or microstructured precision products are injection-molded with minimal wall thicknesses of 20 µm, aspect ratios of more than 30 and structural details down to 200 nm. Materials applied in micro injection molding are PMMA, POM, PA, PC, PE, PEEK, PSU and LCP.

Many applications require material properties which polymers cannot provide. For the casting of metal microstructures molded plastic microstructures are embedded into a ceramic mass. During burning of the ceramic mass to a mold the plastic microstructures are lost. Into the hollow ceramic mold the molten metal is injected. After cooling down the metal micro-parts are unbedded by dissolving the ceramic mold. Another technique is powder injection molding which is an economically viable process for the manufacture of complex shaped metal or ceramic parts in large series. A micro powder injection molding process (microPIM) is currently being developed at FZK /8/.

In the microPIM process, metal or ceramic powders are mixed with a binder system and injected into the mold which contains the microstructured mold inserts. In order to achieve a good filling of the mold inserts, feedstocks with low viscosity and evacuated injection molds such as for thermoplastic micro injection molding are required. The molded parts are further processed in a furnace to remove the binder system. Subsequently, they are sintered under defined atmosphere to achieve solid micro-parts.

The development of the microPIM has been started by using powders and binder systems which are already in service for macroscopic applications. The manufactured micro-parts have a theoretical density of up to 98% while the linear shrinkage varies in a range of 15 to 22% depending on the composition of the feedstocks. Nominal sizes of the final micro-parts have been obtained within a tolerance of ± 0.3 to 0.7%. Due to the smaller particle size of the ceramic powders, the molded structures show a better surface quality compared to the metal structures.

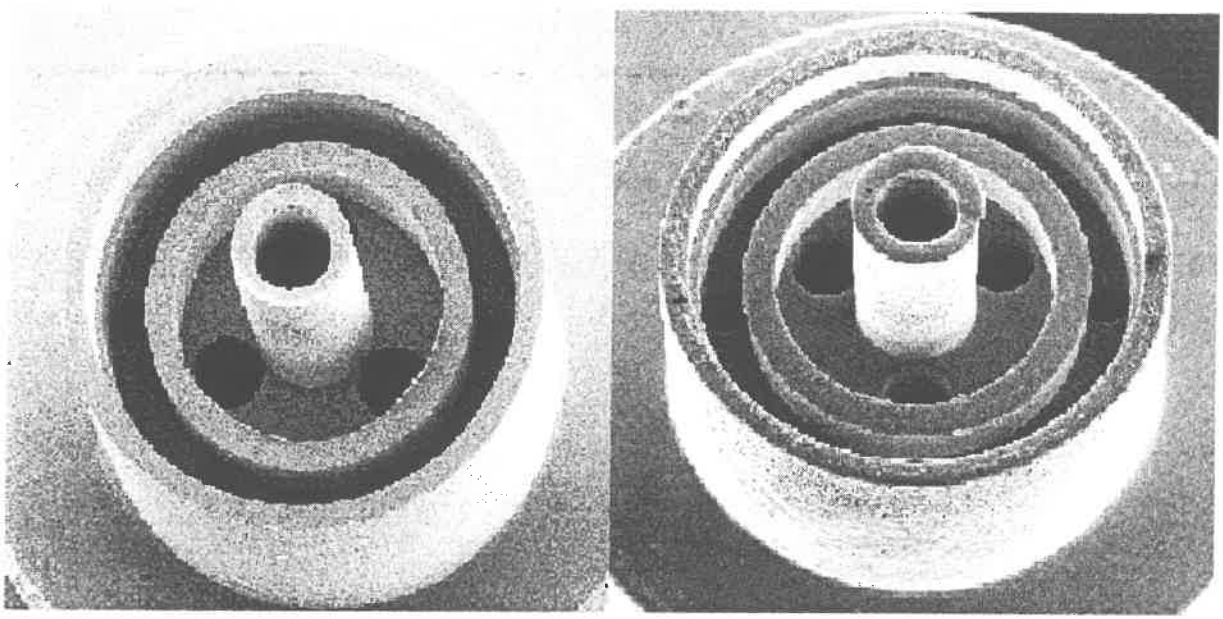

Figure 6: Micro-turbine housing as an actuator component for a prototype of a cardiac catheter system manufactured by micro injection molding (left hand) from PMMA and by micro investment casting (right hand) from Stabilor G™ (a gold-silver-copper alloy supplied by Degussa AG).

The central cylindrical structure has a height of 1 mm with a wall thickness of 116 µm.

Examples of Molded Microstructures

Examples of molded micro-components using mold inserts made by mechanical micromachining are housings for micro fluidic systems (Figs. 4 and 5) or micro-components for cardiac catheters (Fig. 6). Test structures made by micro powder injection molding using fine powders (Al_2O_3, 98% density) are shown in Fig. 7.

Conclusion and Outlook

Mechanical micromachining is an inexpensive approach for the manufacture of microstructured mold inserts providing structure variety and sufficient accuracy for many applications. The replication of the microstructures by injection molding or hot embossing has been demonstrated in a prototype or small series for various microsystems components, namely fluidics. For a large-scale production of microstructures, progress can be achieved in structure variety, in the use of materials for mold inserts and products and in the corresponding variation of the molding process. Especially for injection molding with filled plastics or for powder injection molding there is the need for more wear-resistant microstructured mold inserts. Thus, the machining of hardenable steel is a key technology for the increase of the material variety and for the realization of applications using molding techniques. The long-term aim is to establish the mold

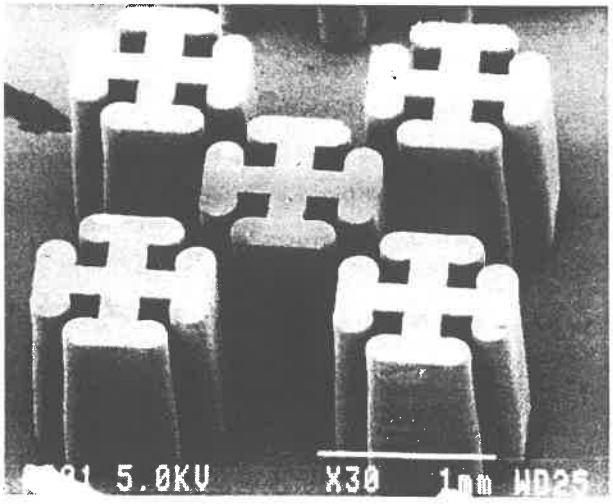

Figure 7: Column-like test structures made of Al_2O_3 molded by powder injection molding using mold inserts made by mechanical machining with a 250 µm diameter milling tool.

machining and the replication of high aspect ratio microstructures as an industrial standard process for future microstructure production.

Glossary of polymer materials

LCP	Liquid crystal polymers
PA	Polyamide
PC	Polycarbonate
PE	Polyethylene
PEEK	Polyetheretherketone
PMMA	Polymethylmethacrylate
POM	Polyoxymethylene
PSU	Polysulfone

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Diamond Turning of Molds for Precision Aspherical Lenses

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University of Bremen, Germany

Abstract

The fabrication of precision molds for the molding of optics is one of the domains of single-point diamond turning. In this paper we outline the range of applications - from rotationally symmetric surfaces to micro-structured and freeform surfaces - and try to identify future needs.

1 Indroduction

Replication techniques play an increasingly important role in the optics industry. Wherever identical units have to be produced in large quantities - lenses for video camera objectives, CD player lenses, Fresnel lenses for overhead projectors, retroreflective tapes etc. - replication most often proves to be a cost effective alternative compared to the manufacture of individual parts. Provided the replication process does not degrade surface integrity, the quality of the molded parts cannot be higher than the quality of the mold itself. Hence, mold fabrication is the crucial first step of the production cycle.

Precision molds may be devided into the following classes:

- molds (with negative form) used for direct molding of optical elements, e.g. injection molding of plastic lenses, embossing, or hot pressing of glass lenses,
- masters (with positive form) which are replicated by a galvanoforming process, e.g. nickel electroforming, the replicated part being the actual mold,
- mandrels (with negative form) used for galvanoforming or replication in fibre reinforced plastics.

Depending on the nature of the replication process, molds may be used in low temperature (20°C – 100°C), medium temperature (100°C – 300°C) or high temperature (300°C - 800°C) applications. Some of the mold materials in common use, e.g. hardened steel, silicon carbide and glass, must be ground and polished, others like electroless nickel, brass, aluminum or copper can be diamond turned. It should be understood that a discussion of diamond machining of precision molds within the scope of this paper can by no means be exhaustive. The examples presented here were collected from the work of the LFM Laboratory for Precision Machining and should only be regarded as a brief introduction into this exciting and diversified field.

2 Rotationally symmetric surfaces

The diamond turning technology is well known for the comparative ease with which aspherical surfaces can be generated in metal substrates. Fig.1 shows a drawing of a typical insert for injection molding of small aspheric plastic lenses. The substrate material is stainless steel; the protrusion that carries the optical surface is plated with an electroless nickel layer about 100µm thick. Electroless nickel is chosen because it is the hardest known material that can be diamond machined yielding an excellent surface roughness < 3nm rms. However, even an innocent looking mold like that of fig.1 can impose unexpected manufacturing problems due to the limited arc available on the radius tool (usually 90°) and the large clearance angle needed to avoid back cutting with the clearance face (cf. fig.2).

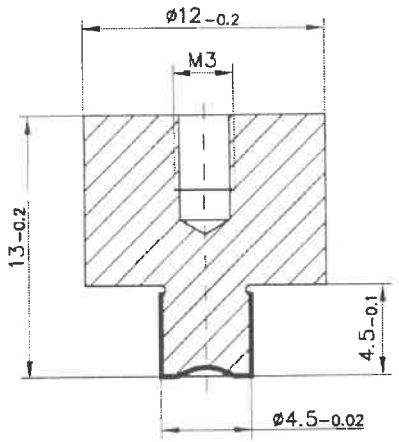


Figure 1: Electroless nickel mold for mild asphere

Sometimes, the tool must be tilted (causing a positive rake) which requires a different kind of cutter compensation, since the arc appears to be elliptical in projection and the contact point escapes from the horizontal plane when the cutting process moves away from the center of the part. If such complications arise, it is imperative to measure the generated contour (e.g. with a profiling instrument or a coordinate measuring machine) and correct the part program accordingly until specifications are met. It is also imperative to cut the outer diameter of the mold insert together with the optical surface in one set-up so that centering and tilt erros are eliminated.

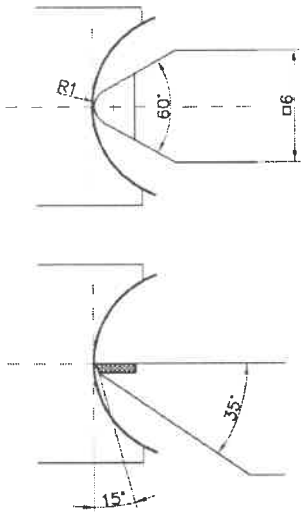
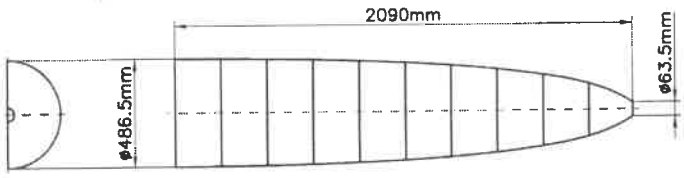


Figure 2: Diamond turning of concave aspheres



Segments : 10
Contour : inclined parabola
Material : aluminium AlMg3

Figure 3: Ballon Air Cherenkov experiment. Mandrel for Winston-collector

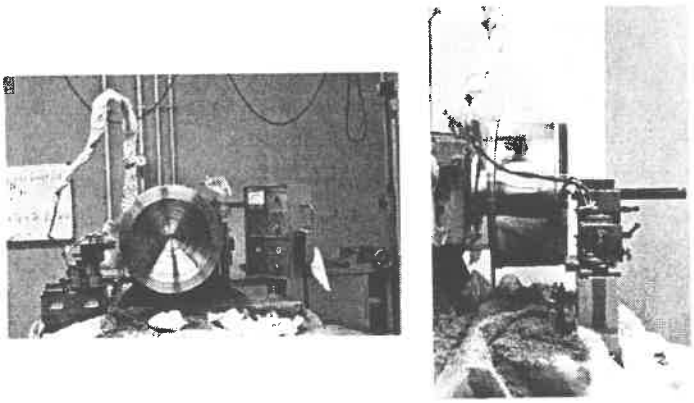


Figure 4: Ballon Air Cherenkov experiment. Diamond turning of mandrel segments

Another extreme of generating rotationally symmetric mold surfaces is the fabrication of mandrels for space-borne X-ray or UV telescope mirrors or for collectors for the detection of Cherenkov radiation emitted by energetic cosmic ray particles penetrating the earth's atmosphere. Often, large mandrels have to be assembled from smaller units which must all fit together within tight tolerances. An example is given in fig.3 showing a Winston collector mandrel composed of 10 aluminum half-shells. In order to secure perfect match of the segments, the material must be stress-relieved after premachining and mounted without clamping distortions. Before the final cut is done, the absolute size of the parts must be evaluated in order to avoid undercutting. Each segment must precisely be balanced with counterweights on the diamond turning machine (fig.4). The light-weight collectors were replicated from the completed mandrel in fibre reinforces epoxy resin.

3 Linear structures

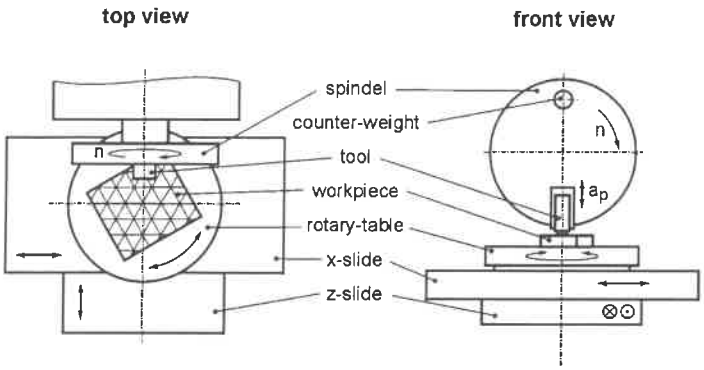


Figure 5: Fly-cutting of gratings and prisms

Linear structures like gratings and prisms can be generated with a V-shaped diamond tool in a fly-cutting set-up illustrated in fig.5 [1]. The mold is mounted on a rotary table which is moved relative to the fly-cutter with the x- und z-slides. For setting the depth of cut either a y-axis is needed or the tool holder must be mounted on a rotating slide. The angular orientation of the diamond tool must be verified prior to cutting. If three systems of parallel grooves should intersect in common points (cf. fig.6), alignment of the diamond tool with respect to the fly-cut plane is critical. Depending on the total length of the grooves, machining can last several days. Since only prolate prisms can be generated in a cutting process, the actual mold is usually derived from the master by galvanoforming.

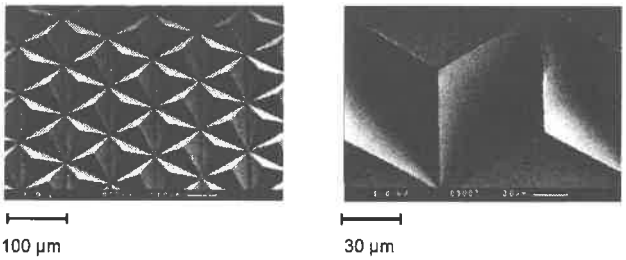
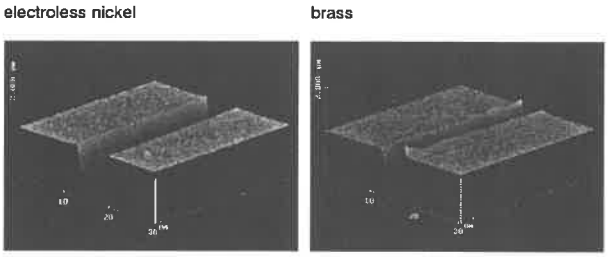


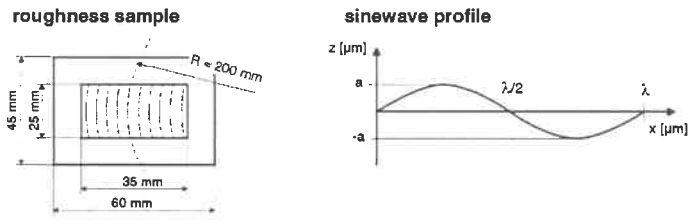
Figure 6: Retroreflective tape with microprisms



process:	plunge cut
cutting speed:	v_c = 100 mm/min
tool nose radius:	r_ε = 5 µm

Figure 7: Material response

An important parameter in fly-cutting of grooves is the plasticity of the material. Fig.7 compares the burnishing of different materials along a plunge-cut groove. As is evident from the scanning force microscope images, material sideflow of electroless nickel is almost negligible compared e.g. with brass. Therefore, a relatively hard and homogeneous material like electroless nickel or nanocrystalline copper should be selected, if a good definition of corners and edges is desired.



manufacturing process

off-axis distance:	R ≈ 200 mm
feed:	f = 0.25 µm / rev.
depth of cut:	a_p = 5 µm
spindle speed:	n = 250 rpm
tool nose radius:	r_ε = 15 µm

roughness

amplitude:	a = 5 µm
wavelength:	λ = 100 µm
average roughness R_a:	$R_a = 2\,a / \pi = 3.183$ µm

Figure 8: Roughness standard with sinewave profile

Unfortunately, cutting edges of diamond tools can only be ground and polished to simple shapes. Hence, the groove profiles generated in a fly-cut operation according to fig.5 can only be circular, V-shaped or prismatic. Sometimes, however, a small curvature of the grooves can be tolerated. In this case, linear patterns may be generated by a turning process, if the part is mounted at a large off-axis distance. As an example, this method was applied in the production of masters for roughness standards with sinewave profiles (cf. fig.8). Likewise, molds for small cylindrical lenses (even with a non-circular cross-section) can be diamond turned at large off-axis distances.

4 Fresnel structures

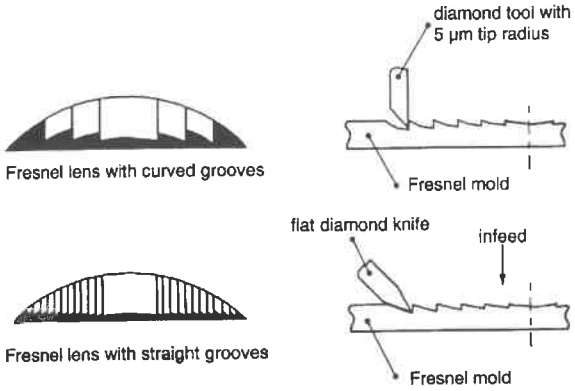


Figure 9: Fresnel lenses and their generation

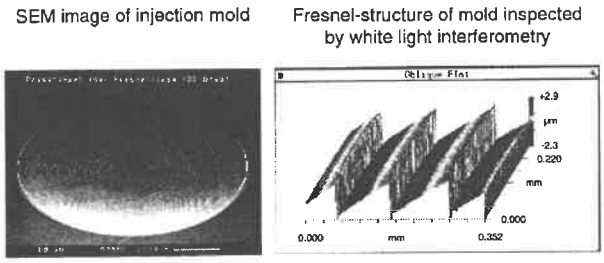


Figure 10: Injection mold for bifocal intraocular lenses

In many cases diamond turning is just a faster and more deterministic way of creating an optical surface but could, in principle, be substituted by polishing. There is, however, no reasonable alternative if discontinuous surfaces are concerned, e.g. prismatic or Fresnel structures. Fig.9 shows two common techniques for generating Fresnel grooves, i.e. contouring the individual groove profiles with a very small radius tool (typically 5µm nose radius), and plunge cutting of grooves with straight profiles. One of the early applications of the contouring technique is the fabrication of molds for bifocal intraocular lenses. Such lenses exhibit shallow grooves (2µm to 4µm deep) with hyperbolic profiles (cf. fig.10). For contouring only two programmable axes are required, and tool alignment is fairly simple. On the other hand, only a small volume of material can be removed, since small radius tools wear easily.

In addition to two linear slides, the plunge-cut method requires a rotary axis for setting the groove angle. The tip of the pointed knife tool must be aligned to meet the axis of the rotary table. Moreover, the cutting edge of the tool must be parallel to the x-direction in the zero degree position. Machining parameters have to be adjusted to balance conflicting requirements: Cutting forces must be small enough to avoid chatter; however, the depth of cut cannot be made arbitrarily small due to the finite stiffness of the turning machine. Damage of the tool tip and the cutting edge is always a risk in plunge-cut operations. Chip removal can be a problem with deep grooves. Despite these difficulties, the plunge-cut technique is widely used for the fabrication of molds for large Fresnel screens, mostly with soft materials.

5 Hybrid structures

An extremely difficult task in mold fabrication is the generation of hybrid structures incorporating both ordinary aspheric sections and Fresnel grooves with large aspect ratio and aspheric contours. Hybrid lenses with TIR (total internal reflection) elements are needed for light concentrators and for imaging systems with very small F-numbers. Molds of this type cannot be turned with just one diamond tool. Fabrication of a mold for the lens shown in fig.11 required four different diamond tools with different alignments. Six CNC-programs had to be written. A natural limit is approached if the incuded groove angle is less than about 30°, since narrow diamond tips become increasingly brittle.

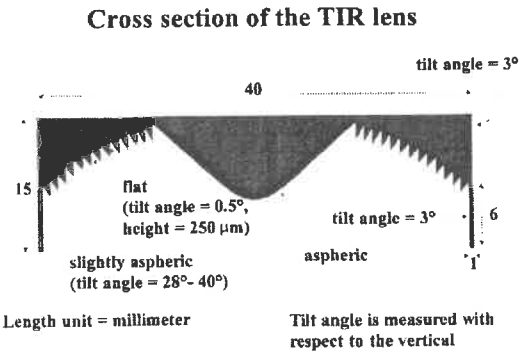


Figure 11: Hybrid lens

6 Asymmetric surfaces

A new challenge in mold making is the generation of non-rotationally symmetric surfaces. One approach is the fast tool servo concept [2]. Recently, attempts have been made to extend the stroke of tool servo systems into the millimeter range which would make the concept applicable to a much larger variety of geometries [3]. Another approach is diamond milling with a fast spinning tool which can be moved back and forth with respect to the angular position of the slowly rotating workpiece spindle (cf. fig.12). This method was used for the production of a mandrel for galvanoforming of non-rotationally symmetric reflectors (cf.fig.13) used for large screen movie projection. In contrast to a diamond turned surface, a milled surface exhibits tiny pits whose size and depth depend on the rotational speeds of the milling tool and the workpiece, the milling and tool radius and the infeed motion [4]. If a very smooth surface is required, machining may last several hours or even days. An advantage of diamond milling is a surprisingly long tool life despite great depths of cut.

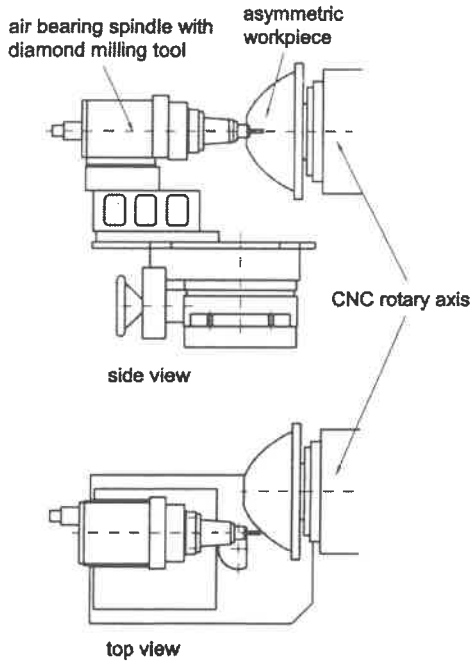


Figure 12: Milling of asymmetric mandrel

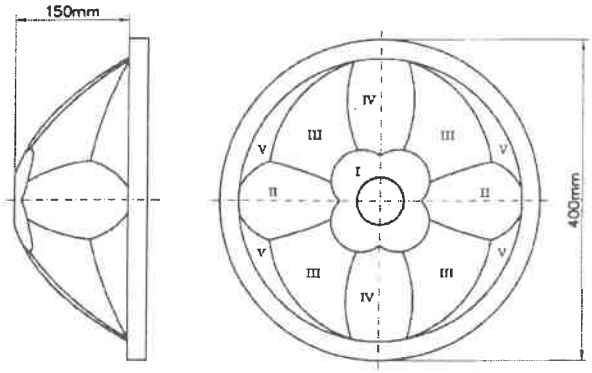


Figure 13: Mandrel for asymmetric reflector

If instead of a radius tool a V-shaped tool is employed, diamond milling also allows the generation of Fresnel grooves superimposed onto asymmetric surfaces [5]. The machining set-up is essentially the same but requires at least one additional rotary axis for controlling the angular position of the milling tool (cf. fig.14). There is a vital interest in molds of this type in the car lighting industry.

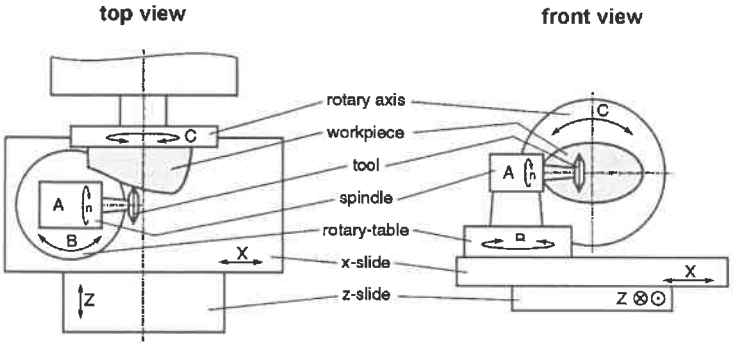


Figure 14: Fly-cutting of Fresnel zones on freeform surfaces

7 Concluding remarks

Diamond machining has developed into a powerful tool for manufacturing of precision molds ranging from small aspheric inserts to large asymmetric mandrels. An important future challenge is multi-axis diamond milling of complex surfaces with optical or near-optical quality. Another challenge is the development of diamond machinable materials or coatings for molding at high temperatures. Last but not least, there is a lack of non-destructive testing techniques for structured surfaces with large aspect ratios.

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Patterning Submicron Features using Broad Beam Neutral Ion Etching

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Patterning submicron features is required in data storage, microelectronics, MEMS, micro-optical devices (diffraction gratings), etc. In all these applications, features are usually patterned using direct writing on photoresist (laser beam recording) or lithographic techniques. In some of the more prevalent devices (e.g. compact discs and digital versatile discs or DVDs), the manufacturing process includes pattern generation on a master, creation of a durable stamper, and injection molding of replicas.

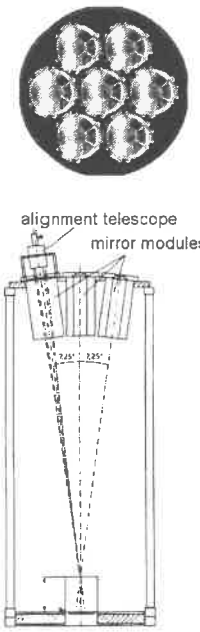
The purpose of this research is to investigate all processing steps involved in obtaining submicron features on nickel DVD stampers and their replicas, using a new method developed for CD stamper manufacturing, called Precision Stamper Manufacturing (PSM). In this new process, nickel substrates are ion machined using a negative tone photoresist mask. The advantages of Precision Stamper Manufacturing, compared with the traditional CD stampers manufacture procedure, consist of reduced hazardous waste, improved productivity and lower production costs.

The main steps involved in PSM are photoresist patterning, ion machining, and photoresist removal. A 150 mm diameter, 0.3 mm thick nickel disk is first coated with negative tone photoresist and softbaked. Direct writing is then used in order to record the information in photoresist. The photoresist is exposed selectively using a switched, focus laser beam. After hardbaking, the photoresist is developed. The exposed areas of the photoresist remain on the wafer, while the unexposed ones dissolve in developer and wash away. CD (DVD) features in photoresist are obtained on the nickel substrate at the end of the development step. The developed sample is then ion machined, using a broad neutral argon ion beam. Ion machining is used to transfer the pattern in photoresist to the nickel substrate. The photoresist remained on the top of the nickel features after ion machining, is then chemically removed .

The influence of photoresist thickness, undercut, baking temperature and duration, exposure beam power , development time, and other parameters that occur during PSM, on the final feature geometry have been studied. Also, the effects of rotation, cooling, and substrate tilting during ion machining, on feature's profile and on etching rates have been investigated. Experiments performed at different machining angles proved that both the feature's profile and the etching rates vary with the beam incidence angle. Another issue outlined here is the pattern transfer from photoresist to the nickel substrate, taking into consideration the secondary effects of ion machining. Photoresist cross-linking due to overheating and ion bombardment during ion machining makes it harder to be removed, especially from submicron features. Photoresist removal using chemical and oxygen plasma etching processes were tested. Removal chemistry and the influence of feature size and sample processing on removal are also analyzed.

The samples were systematically analyzed after development, ion machining and removal, to evaluate the CD (DVD) features. SEM and X-rays were used for a qualitative estimation of the features, while AFM supplied both quantitative and qualitative data. SEM pictures and AFM diagrams of DVD features (Fig. 1) provide information about the geometry and the dimensions of the features. X-rays analysis was used to indicate either the presence or the absence of photoresist.

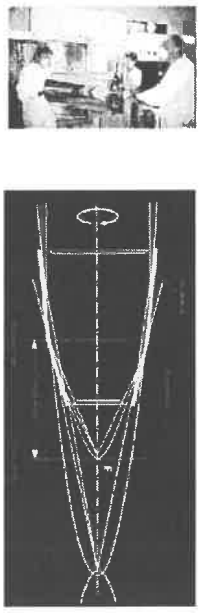
Fig. 2 illustrates photoresist features, obtained at the end of the development step. The features appear sharp, well defined, with wall angle of 76 degrees and very low undercut. Photoresist thickness can be controlled during coating, by varying the photoresist dilution and the spin speed. The feature width is set by the exposure beam power (higher beam power produces wider features). The undercutting,



Mirror shell data	
Geometry	Wolter type I
Number of modules	7
Mirror shells per module	27
Diameter	76 - 163 mm
Length	300 mm
Radial shell distances	~ 1 mm
Wall thickness	0.2 - 0.4 mm
Material	nickel
Focal length	1600 mm
50% energy conc. (on-axis)	< 30 arc sec
Surface microroughness	< 0.5 nm rms

courtesy of Carl Zeiss, Oberkochen

Figure 7: ABRIXAS (A BRoad-band Imaging X-ray All-sky Survey). Telescope design

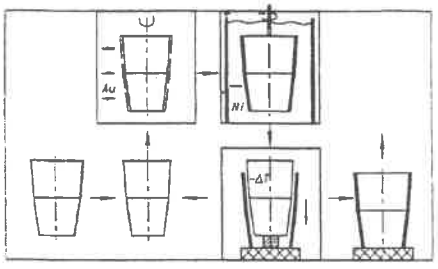


Mirror shell data	
Geometry	Wolter type I
Number of mirror shells	58
Diameter	306 -700 mm
Length	600 mm
Radial shell distances	1 -2 mm
Wall thickness	0.5 - 1 mm
Material Core Surface	 AlMg alloy electroless nickel
Focal length	7500 mm
50% energy conc. (on-axis)	< 6 arc sec
Surface microroughness	< 0.4 nm rms

courtesy of Carl Zeiss, Oberkochen

Figure 9: XMM (X-ray Multi mirror Mission). Ttelescope design

the relatively high density of nickel jeopardizing the total weight allocation of the mission. Unfortunately, the internal stresses created in the substrate during electrodeposition tend to degrade the form accuracy of the mirror surfaces, if the wall thickness is very small. Therefore, a major effort was made to identify and control the bath parameters correlating with internal stresses.



1 Mandrel production and acceptance
2 Mandrel cleaning
3 Mandrel gold coating (PVD)
4 Nickel electro-deposition
5 Mirror shell release by cooling
6 Free mirror shell, ready for testing

Figure 8: Nickel electroforming process for ABRIXAS mirror shells

- **Mandrel gold coating**
  - surface treatment ⇒ cleanliness, moderate adherence of gold layer
  - coating process (PVD) ⇒ uniformity and thickness of gold layer
- **Nickel electroforming**
  - operating temperature: 22 ± 2°C
  - current density: < 30 A/m^2
  - deposition rate: < 3 µm/h
  - tensile stress: < 10 MPa
- **Uniformity of deposited Ni-layer**
  - goal: better 2.5% along taper section and better 1% around circumference
  - solution: suitable shaping and positioning of the electrodes adjusted circulation of electrolyte
- **Mirror shell release**
  - cooling down to -30 to -50 °C

Table 2: Production of ABRIXAS mirror shells

6 Replication in carbon fibre reinforced plastics

In the development stage of the X-ray telescope for the XMM mission replication of the mirror shells in light-weight carbon fibre reinforced plastics has also been investigated but had to be abandoned due to outgazing of the epoxy resin in vacuum with subsequent print-through of the carbon fibre tissues. Nevertheless, it could be shown that the tight figure and surface roughness tolerances of the mirror shells could be met.

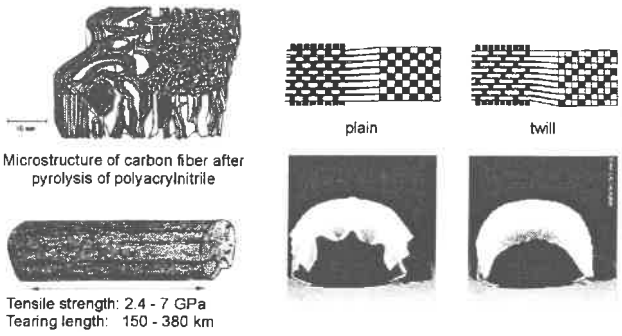

Microstructure of carbon fiber after pyrolysis of polyacrylnitrile
plain
twill
Tensile strength: 2.4 - 7 GPa
Tearing length: 150 - 380 km

Figure 10: Carbon fiber tissues

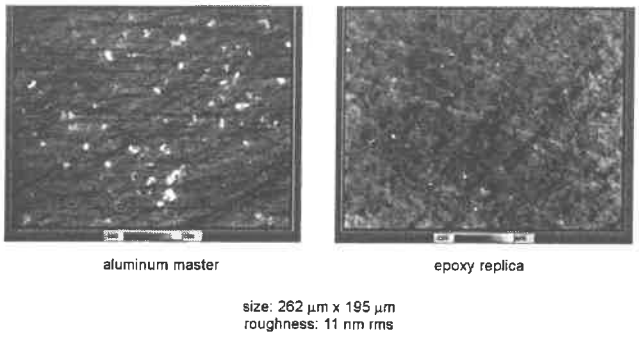


Figure 11: Replication in carbon fiber reinforced plastics (CFRP). Reproduction of microtopographic details

High qualitiy replication in reinforced plastics requires overall hygiene in all stages of the process, careful preparation and application of the laminate without streaks, inclusions or bubbles and curing of the resin at constant ambient temperature. If the replicated surface exhibits marked curvatures, the texture of the fibre tissue is important (cf. fig.10). As can be seen from the white light interferometric images of an aluminum surface and its epoxy replica shown in fig.11, microtopographic details are well preserved in the replication process.

7 Conclusion

All precision replication techniques discussed here do preserve microtopographic features on the nanometric scale. However, macrogeometry is not easily maintained. Processes carried out at (near) ambient temperature like electroforming and replication in reinforced plastics can preserve figure accuracy, if residual stresses can be controlled and deformations caused by separating the replica from the mold can be avoided. Molding techniques applied at non-ambient temperatures systematically lead to figure errors due to volume changes during cooling and / or curing which ideally are homogeneous, if isotropic environmental conditions can be provided.

Above all, repeatability of the molding process is a prerequisite for the development of any kind of optimization stategy. Thus, mold fabrication, replication and testing are intimately interlinked and sometimes must be iterated several times before satisfactory results are achieved.

Acknowledgment

We gratefully acknowledge the information provided by Dr. W. Döll from the Fraunhofer-Institut für Werkstoffmechanik, Freiburg, on the shrinkage of glass lenses and by Dr. Y. Chen from Carl Zeiss, Oberkochen, on the fabrication of X-ray telescope mirrors.

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Replication of High Fidelity Surface Relief Structures

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There are several methods currently available for replicating high-quality patterned optical surfaces. This paper investigates the optical performance of replicated imaging quality diffraction gratings, interferometric encoders, and performance enhancing surface relief structures manufactured with ultraviolet curable photopolymers (UVPP) as an integral part of the replication process. Through the development of a UVPP replication process, fabrication times of the desired optical components are decreased while product quality is maintained, and in many cases increased. Attractive low cost replication based solutions to several optical manufacturing problems are discussed.

Review of Existing Technology

Replication technology employing embossing, molding, both injection and epoxy, and etching has been used for years in the production of surface relief optical components ranging from the visually pleasing, but low quality, credit card holograms to imaging quality diffraction gratings used in high resolution optical systems. Each of these technologies has provided cost-effective solutions for the production of multiple components from a single master optic. Depending on the desired component's requirements regarding cost, quality, production volume, substrate shape, etc., one technology would typically stand out as the obvious choice for manufacturing.

Embossing technology is typically used to produce relatively low quality surface relief structures in high volume at low cost.[1] Holograms such as those found on credit cards and software boxes are examples of the type of grating that can be manufactured using embossing.[2] Both the low cost and quality are due in part to the materials available for embossing. This technology applies heat and pressure to transfer surface relief microstructures from stamping rollers into a plastic substrate. Specifically, the substrate, which is typically a thermoplastic foil, is heated above its glass transition temperature

(T_g), pressed between embosser plates or rollers, and allowed to cool before release. Embossing is capable of producing submicron structures when properly designed equipment is used.

Due to the inherent limitations of thermoplastics, components produced by embossing lack the requirements necessary for imaging applications.[3] Other issues arise in the macroscopic features of the component. Typically embossed structures are limited to flat surfaces that are used for non-imaging optical systems such as light control optics and visual displays.

Injection molding technology is typically used to produce moderate quality surface relief structures in high volume at low cost. Non-imaging Fresnel optics and compact discs are two examples of injection molded structures. Injection molding provides added flexibility as mounting tabs and other features can be designed directly into the component for easier assembly and alignment. The repeatability of the replicated part is contingent on the control of the injection molding process. Complex microstructures with high aspect ratios can be attainable if proper attention is paid to the thermodynamics of the mold.[1] The constraints on injection molding are similar to that of embossing, where one is limited to thermal polymers, which in many cases do not possess the quality characteristics necessary to produce high fidelity optical components. Moreover, due to the high cost of tooling associated with injection molding, the cost advantage over more conventional manufacturing processes does not become apparent until runs reach tens of thousands.

Conventional epoxy molding technology is typically used to produce moderate to high quality surface relief gratings in low volume at moderate to high cost. Spectrometer and monochromator gratings are two examples of epoxy molded structures. As with injection molding, epoxy molding provides added flexibility as mounting tabs and other features can be designed directly into the component for easier assembly and alignment. The repeatability of the replicated part is excellent when properly controlled processes are in place.

The major constraints on epoxy molding are the long processing times associated with it and the stress induced by the thermal curing cycle. Unlike injection molding where the cycle times can be well below one minute, epoxy curing cycles can run 6 hours

or longer. Long cycle times significantly impact the cost of the component produced. For both single component heat cured epoxy, and room temperature cured exothermic two part epoxy, the thermal stress induced can play a major role in the quality of the final product. Significant care must be taken to factor in the effects of thermal stress in order to produce high quality components.

The photolithography/etching process is typically used to produce high quality surface relief binary gratings in low volume and at high cost. Beam homogenizing[4] and beam shaping diffractive optical elements[5] (DOE) are two examples of binary gratings produced by the photolithography/etching process. This replication technology provides the designer with some freedom of substrate material choices, and is a process that produces good repeatability. With proper process control, feature errors of less than 5% can be achieved.[6] With the use of gray scale masking it is possible to achieve structures that approximate continually curved structures rather than stepped. This technology is often used in the production of diffractive optics for variety of applications that require lightweight alternatives to refractive optics.

The drawbacks of this technology can be severe. Typically the replication process requires a significant number of tightly controlled etching steps in order to produce gratings with enough diffraction efficiency to be useful. Each additional step not only raises the cost of the associated part, but can also have a significant impact on grating quality due to mis-registration of the overlays.

Latest Advance in Replication Technology

State of the art replication technology developed recently at Holographix, Inc. as well as at other companies incorporates ultraviolet curable photopolymers (UVPP) as part of the replication process. This technology incorporates many of the positive aspects of the other major replication technologies without the associated drawbacks. This technology provides a cost-effective way to produce high quality surface relief structures in almost any volume at low cost. There are a number of very attractive attributes of this approach. Most importantly, the UVPP technology enables high-speed production of high quality replicated structures, such as the transmission grating shown in Figure 1. Each replica is produced using UVPPs, which cure within seconds, while at the same

time allowing the replica to stay at ambient temperature, which is why Holographix refers to this process as "cold" forming. Short cycle times mean lower cost, while ambient curing provides low thermal stress and thus high quality components can be attained. Another important attribute of this process is the flexibility it provides the systems designer. As with conventional epoxy replication, virtually any material can be used as the replica substrate; metal, glass, and plastic are all viable materials. Additionally, the process does not constrain the shape of the substrate. Therefore, components can be designed with almost any shape as well as with built in mounting tabs and other features. This flexibility allows for straightforward implementation of replicated structures into production systems. This paper describes the benefits of this replication technology by discussing case studies of three different types of surface relief structures that have been successfully manufactured using the technology.

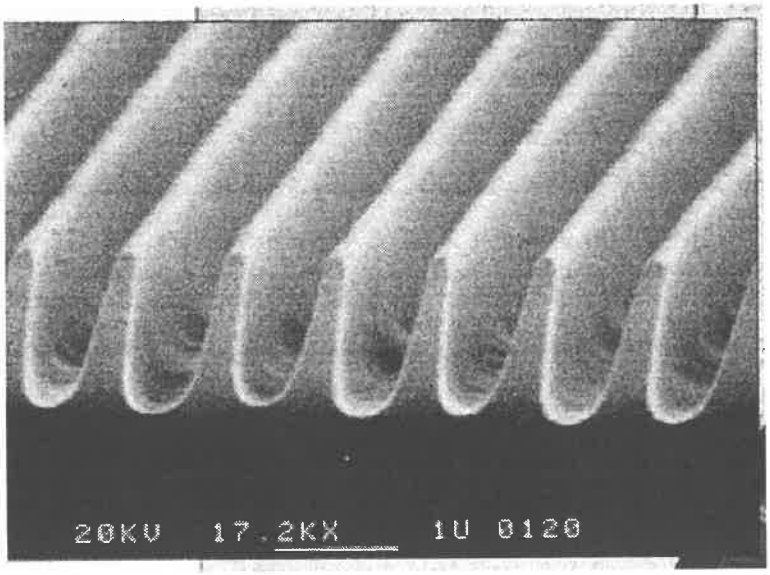

Figure 1 - Replicated Transmission Grating

Case Study #1: Diffraction Gratings For Imaging Applications

Nearly everyone is familiar with the colorful diffraction gratings (holograms) found on credit cards, cereal boxes and software etc. However, more then ever, optical system designers are finding diffraction gratings an attractive alternative to conventional optics for a variety of high quality imaging applications. Surface relief diffraction gratings are used in a variety of commercial devices including spectrometers,

holographic-based scanners, and pulse compression systems to name just a few. In most cases, these systems require high diffraction efficiency as well as preservation of the wavefront quality of the incident light beam. The use of original master ruled or holographically recorded gratings is attractive due to their high quality but is not generally economically feasible when production volumes of more than 5 or 10 units are required. The most economical solution for designs where production volumes are required is replication. However, for the replicated grating to function effectively in the system it must be a high fidelity copy of the original master grating.

Using UVPP technology, Holographix, Inc. manufactures a number of different transmission and reflection gratings for a variety of imaging applications (Figure 2). These gratings are replicated onto both high quality glass substrates and inexpensive polycarbonate substrates. The first step in the production of replicated gratings of this type involves the creation of the surface relief master and stamper tooling. The master can be formed in photoresist using holographic recording techniques or can be formed in aluminum or other suitable material using a high-resolution ruling engine. From the master grating, Holographix, Inc. can produce hundreds of stampers using proprietary stamper generation technology. These stampers are then used to produce hundreds, and in some cases, thousands, of high quality replicas. Thus, tens of thousands of high quality replicas can be made from one master (Figure 3).

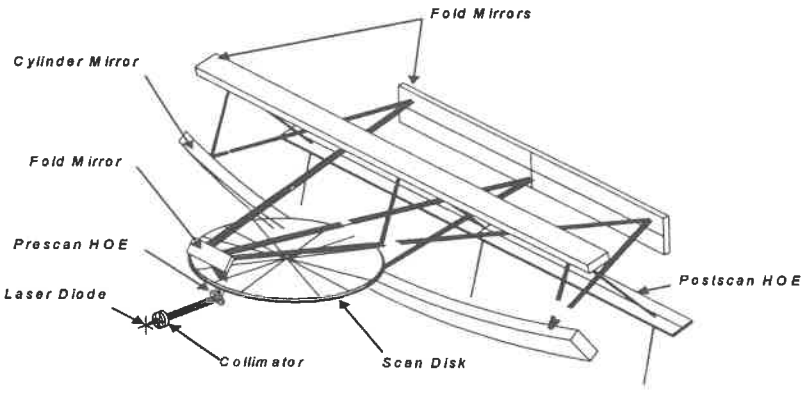

Figure 2 - Holographic Scanning System

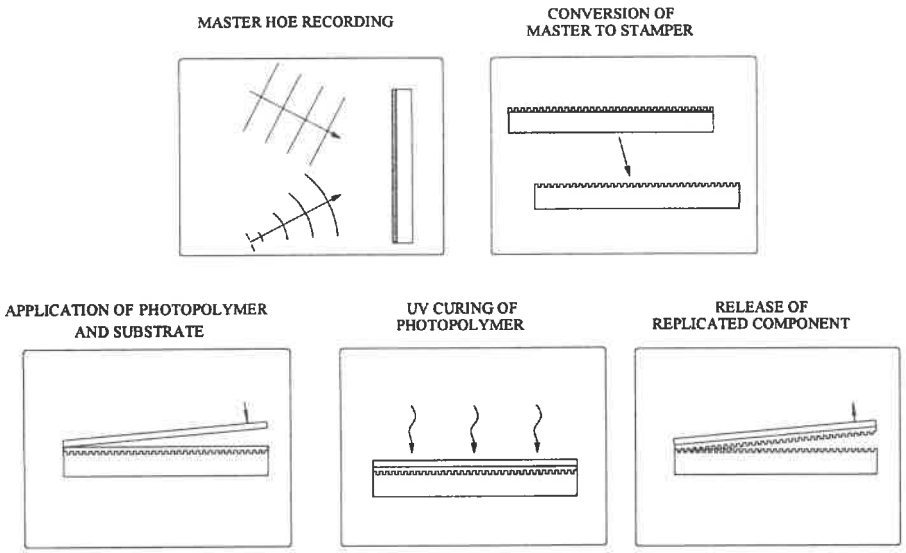
MASTER HOE RECORDING
CONVERSION OF MASTER TO STAMPER
APPLICATION OF PHOTOPOLYMER AND SUBSTRATE
UV CURING OF PHOTOPOLYMER
RELEASE OF REPLICATED COMPONENT

Figure 3 - Cold Form Replication Process

As with other manufacturing technologies, an important factor in the success of the replication approach is the repeatability of the components produced. With proper tooling and manufacturing processes in place, a very high degree of repeatability is virtually guaranteed using UVPP technology. Efficiency studies performed on gratings produced by Holographix, Inc. show that over the lifetime of a stamper, diffraction efficiency variations of less than 2% part to part can be expected (the efficiency is measured as the difference of the diffracted beam energy versus the incident beam energy) (Figure 4). Alignment and wavefront quality have also been shown to be very repeatable part to part. Numerous trials have shown that field replacement of gratings produced at Holographix, Inc. require no re-alignment in most cases to achieve the specified optical performance. This is quite different than that which is experienced when master gratings are used in each system. While master gratings provide comparable wavefront quality to that of the replica, they show more variation in diffraction efficiency from part to part and can be harder to align as they are not duplicates. Therefore, UVPP replication not only provided a significant cost savings, but it also enabled these products to be higher quality and easier to align.

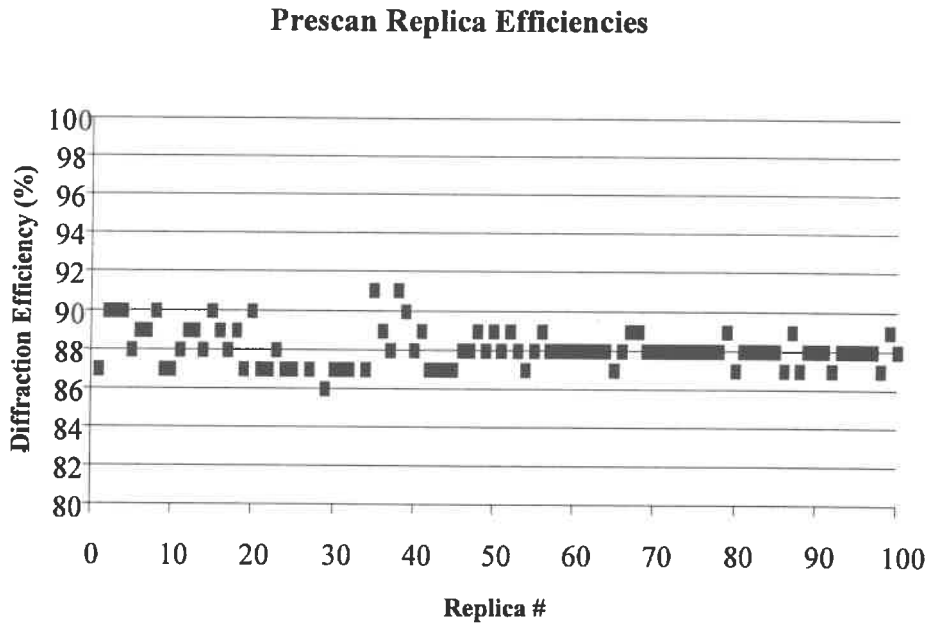

Figure 4 - Replica Efficiency Repeatability

Case Study #2: Interferometric Encoders

A new application for surface relief diffraction gratings has emerged for the precision motion control and measurement markets. In the past, the chrome-on-glass type encoder was the technology of choice to provide position feedback for both linear and rotary motion devices. These encoders are manufactured using photolithography and etching. For very high-end precision motion control, for applications such as semiconductor and metrology devices, Michelson-type interferometers replaced chrome-on-glass encoders to provide the resolution required. Today, a single device called the interferometric encoder (Figure 5) is rapidly replacing these two approaches. This device provides the compactness of the chrome-on-glass encoder with the resolution capabilities of the rather bulky Michelson interferometer.

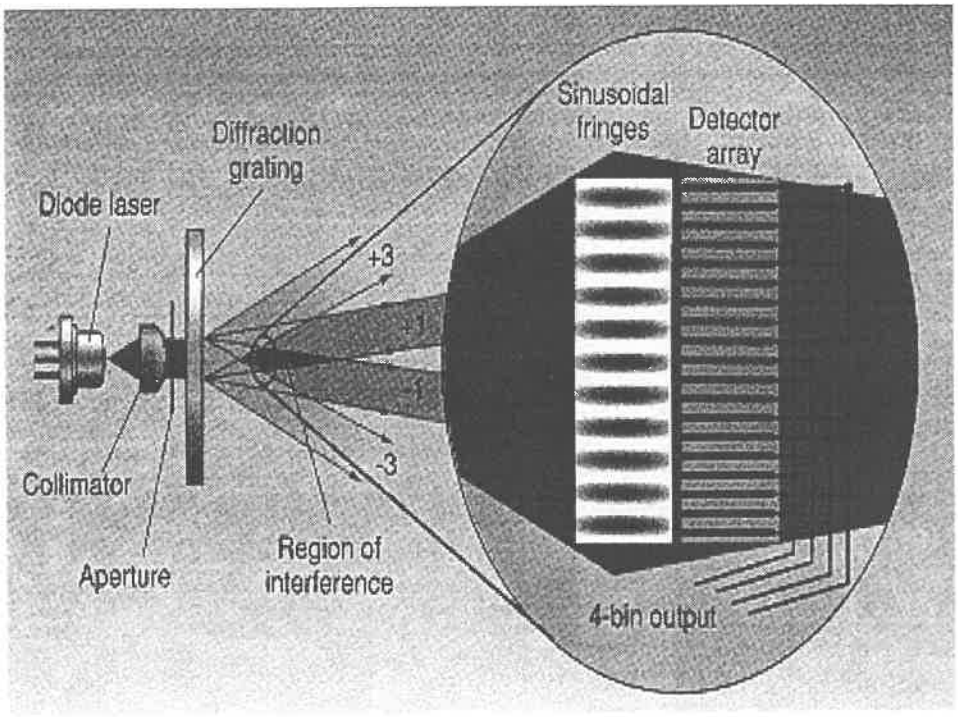

Figure 5 - Interferometric Encoder Assembly (Courtesy of MicroE)

For these encoders to meet the requirements of this demanding application, they must be fabricated to exacting tolerances. The grating's depth and pitch must be rigorously controlled during manufacturing. Errors in the range of 10's of nanometers can cause significant degradation in the encoder's performance. Imperfections in the gratings are also problematic as they can cause dead zones in the encoder where position can not be read. Imperfections on the order of 0.1 mm or greater are generally not tolerated.

Until approximately one year ago, all interferometer encoders were individually manufactured as master gratings. Due to the large number of variables, the mastering process leads to non-repeatability from part to part. This in turn reduces yield and increases the time required to assemble and align the grating into the encoder assembly. Since early 1998, Holographix, Inc. has been successfully using UVPP technology to replicate in a variety of different types of interferometer encoders, both linear and rotary. Holographix and its customers are enjoying high production yields of >95% in most cases for these products. Also, because each master is capable of producing >150 replicas and each replicated grating is an exact duplicate of the master, alignment time of

these gratings into systems has been reduced compared to the alignment of master gratings. Again, going to UVPP replication technology not only provided a more cost effective approach to making the gratings, but it also provided a more repeatable and thus higher quality product than was possible with master gratings.

Case Study #3: Performance Enhancing Surface Relief Structures

Performance enhancing surface relief structures are finding their way into numerous applications ranging from flat panel display manufacturing to broadband anti-reflection surfaces. This is in part due to the recent advances in the production of complex surface relief structures over large areas. Since UVPP technology is capable of producing feature quality and depth equal to or greater than that of etched components at a fraction of the cost, it is in most cases the better choice for production quantities of high quality performance enhancing surface relief structures. Relative to other replication approaches, UVPP provides an important benefit in its capability to function over a wide range of environmental conditions without degradation. This is particularly important for certain applications such as diffusers used with high-energy light sources or holographic anti-reflection (motheye) structures (Figure 6) working under harsh environmental conditions.

Holographix, Inc. replicates a number of different custom structures for a variety of customers using UVPP technology. Applications for these structures include diffusers, both holographic and conventional, LCD alignment wells for flat panel display manufacturing, and motheye structures. Structures ranging in pitch and depth from <100 nm to >100 microns have been successfully produced.

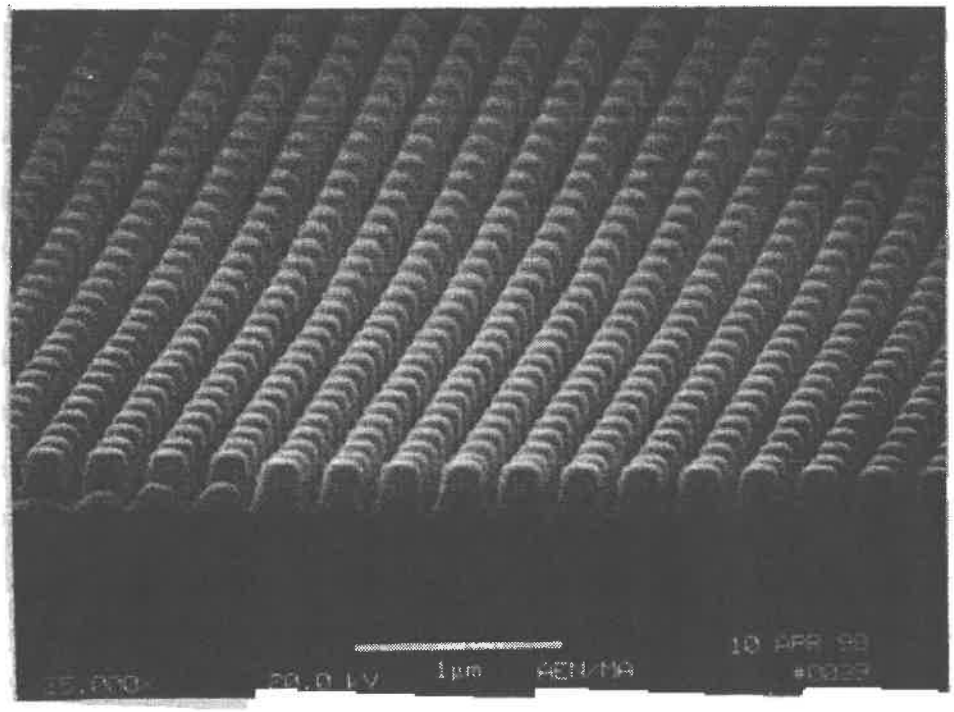

Figure 6 – Replicated Motheye Structure (Courtesy of HLS, Inc.)

Conclusions

As detailed above, there are numerous proven technologies to choose from when selecting a replication approach. However, only UVPP replication technology is capable of producing a wide range of high quality, robust surface relief structures at low cost. This combination makes UVPP technology a very attractive alternative to other more conventional replication technologies. Based on the advantages of UVPP technology, the authors believe that it is the best choice for many applications.

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Replication of Optical Surfaces: Capabilities and Cautions

"Parting is such sweet sorrow" (Wm. Shakespeare: *Romeo and Juliet*)

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1 Reflecting Surfaces

1.1 Requirements

If an optical surface can be generated to a required specification in single or small numbers and used as master 'mold' or 'mandrel' in a surface replication process, initial high investments of effort and cost in making the master are amortized over the total components produced from it. If the master is carefully designed to maintain its surface form and finish characteristics, it can be 'archived' for long-term demand.

An example is the aspheric mirror or lens surface (usually only one aspheric surface is needed in even a compound multi-element lens). The traditional free-abrasive lap-grinding/polishing method is *intrinsically* convergent only for a very restricted set of surface forms: spherical, planar and cylindrical using lap of dimension comparable with the aperture (Gee 1996). An aspheric surface can be generated using smaller laps to accommodate variations of form curvature. However, this sacrifices intrinsic form self-convergence and the process requires considerable effort and cost in controlling the annular distribution of ablation over the surface. The alternative of single point diamond turning is attractive for generating aspheric rotational forms but it is found that economical cut-depths and feed-rates yield an unwanted superposed Fresnel-type grating which may be unacceptable. Where fine finish is required (e.g. R_a ~1nm), post machining polishing tends to degrade the turned form by spherising.

Reasons favoring replication as a manufacturing process include:

Requirements for batch runs/quantities of components or foreseen repeat demands from 'archive' masters.
Surface finish requirements not amenable to single point diamond machining and form not economic/amenable to polishing (of every component) but justified in production of master. (e.g. aspherics).
Pattern arrays of 'features' having small (tens of μm) third axis dimension over an appreciable area (of tens of mm side length) e.g. diffraction-gratings and Fresnel lenses.
Multiple small components and/or arrays of microlenses.
Lightweight metal-based optics for space-borne and/or scanning instruments.
Optical surfaces on materials which do not readily polish (e.g. aluminium).
Arrays of optics to form apertures too large for monolithic manufacture or launch into orbit (e.g. large space telescopes).
Microprobe optics for unusual access (e.g. fuel injector bore inspection).

1.2 Replication: Design Issues

Opto-mechanical system design benefits from early consideration of the replication process so that the substrate shape, structure and mounting can be designed accordingly.

Replication material stability is critical. Cold-curing resins reproduce fine finishes but it is imprudent to assume that large (mm) cured thicknesses of resin will stably maintain the sub-μm form accuracy often required. Chemical shrinkage on curing and differential expansion/contraction due to exothermic reaction effects both need to be considered. As each are functions of bulk, for best form reproduction fidelity, resin thickness needs to be maintained to a an adequately low level by having the replica blank surface follow the finished replica form to within specified limits (over lower spatial frequencies). Replication can then generate fine surface features (to perhaps 1nm roughness) on a blank machined to modest levels of roughness (~1-10μm).

A level of substrate surface roughness is itself desirable for adhesion but this may 'print-through' a thin a layer of resin due to shrinkage. In cosidering optical gratings, Stroke (1967 p.733) suggests shrinkage levels of 1-6%. In respect of components for soft X-ray work, (with shorter wavelengths and generally increased specifications) Michette (1986, pp81-83) reported that for 2.5% shrinkage of replication layers 20-60μm thick with a substrate surface roughness of 300nm, resultant replica surface roughness is 0.3-0.5nm. He also raises the issue of degradation with time as a function of cure-temperature; following an 80°C cure, roughness increased an order faster than at 40°C.

1.3 Coatings for Replication Processing

For optically reflecting surfaces, Hass and Scott (1949) considered the relative merits of silver and aluminium, each with good reflectivity across the visible spectrum. Silver has the higher reflectivity but it incurs greater granularity when vapor-deposited (and this increases with film thickness). Its lower extinction coefficient requires a higher thickness for opacity, so aluminium was favored and the poorer adherence of silver was later turned to advantage as a parting agent (Hass 1955).

For near infrared applications, gold offers favorable spectral characteristics but poor adhesion. However, proprietary techniques permit it to be both ruled and used in replication.

Investigations into coatings for protecting aluminium favored silicon monoxide for corrosion and abrasion resistance (Bradford, Erbe and Hass 1959).

1.4 Mirror Replication by Electroforming

Early electroforming replication work was used to manufacture retroreflective tetrahedral mirror arrays from 'cube-corner' prisms, requiring three mutually orthogonal facets, any departure being compounded in the output beam over three reflections. For arc-minutes of output beam divergence, prices are modest but performance to 1 arc second may cost two orders more.

Goldberg (1948) electroformed copper onto a 3-inch (75mm) tetrahedral prism which had been chemically coated first with silver as the cathode for the copper-plating bath. The prism master showed 2s divergence and the best replica reflector performed comparably with a prism of 5s divergence at distances out to about 2km. Mechanical distortion of the replica was initially a problem and later the (open) base of replicas was supported by a copper disc. The prism 'mold' was reported good for 50 replicas and cost of the final optic about 1/6th that of the equivalent glass prism.

Hass and Erbe (1954), from the same lab., later mention the use of electroforming for making metal replicas of trihedral prisms and mirrors up to 60 inches in diameter for applications such as search-lights (requiring near-collimation over distances of several km.).

Electro-deposition was also used in conjunction with vapor-deposited metallic coatings as an alternative to the epoxy replication process described in section 1.5 and is considered there further.

1.5 Replication of Mirrors by Metallic Coating and Epoxy (or alternatively Copper)

Hass and Erbe (1954) give details of replicating a convex glass master commencing with a 20nm flash coating of silver, followed by a half-wave layer of silicon monoxide and then a coating of aluminium (deposited heavily to provide adhesive keying). Onto this was poured epoxy, filled with silica to reduce shrinkage. After parting, the silver was removed by nitric acid.

Where a more durable backing is required for higher temperatures, an alternative process they describe is the same as far as the aluminium deposition stage. Then, upon the aluminium, a further layer of silicon oxide is deposited followed by a layer of nickel (the second SiO layer inhibiting diffusion between the two metals). A thick copper base is then electrolytically deposited onto the nickel as described Section 1.4.

For a concave replica, this technique requires a convex master which is not so readily made or tested, particularly if large and/or deeply aspheric, (requiring a wide aperture convergent reference test-optic). An alternative two-stage replica process was developed for producing f/1-f/2 mirrors using concave glass mirrors as masters from which convex sub-masters were replicated (Bradford, Erbe and Hass 1959). The concave master was coated with 20-30nm of silver or copper and then a 300nm layer of SiO fast evaporated onto this (in 2 minutes) followed by epoxy, as in the single step process above (Hass and Erbe 1954). This produced an SiO-protected epoxy convex surface (without the aluminium reflective layer) to be used as the (sub) master from which concave replicas were produced as in the earlier single-stage processes.

2 Replication of Diffraction Gratings

2.1 Requirements

The diffraction grating is a prime candidate for replication due to the considerable time and effort required to generate an original. Ruling a grating may take many days to complete after 1-2 days for setting up the diamond tool in a series of ruling-trials and allowing the machine/environment to thermally stabilize. A grating is very easy to test interferometrically and there have been only a few machines consistently capable of approaching diffraction limits in accuracy, requiring groove placement to within tens of nanometres (and periodic errors within sub-nanometre amplitude limits). Maintenance of performance requires scrupulously careful mechanical design, electronic/interferometric control and highly skilled dedicated manpower to construct and maintain the machine in adjustment, with invested down-time periods for reworking ways, bearings etc.

Toward the end of the last century, the ruled width (and thence resolution, which is directly proportional) was increased substantially from 50 to 150mm achieved on three similar engines built to the design of H A Rowland (by W Schneider, constructor and operator) at Johns Hopkins University, Baltimore, MD. These machines passed into the successive supervision of J.Anderson, R.W.Wood and J.Strong (Stroke 1967) with W Perry maintaining and operating them. During a period of some fifty years, while dispersive spectroscopy remained the province largely of university spectroscopy labs and astronomical observatories,

the labs with such machines kept pace with demands by providing original rulings. Gratings above 4-inch (100mm) width between first and last grooves could be reliably ruled by only very few.

Two such machines were built by A.A.Michelson (1927 pp99-103) at the University of Chicago. Using parts of one of these, at the MIT Spectroscopy Lab., G.R.Harrison pioneered the use of the interferometer for automatic feed-back control of groove-spacing and ruled 250mm wide gratings (Harrison and Stroke 1955). Two further machines of 450mm and 650mm capacity (Harrison 1973) were built using commercial machine bases (Moore 1970); the ruled width was largely to meet the needs of astronomy. Since groove length is comparable with ruled width and ruling tool velocity is limited (to about 0.2m/s), the required time to rule a master is proportional to its aperture area (i.e. to the square of ruled width) and full-width ruling-times could be a week or more. Without replication, the availability of large gratings sufficient even for astronomy would have been severely limited.

The coming of spectrometric emission and absorption chemical and biochemical analytical techniques created increasing demand for smaller (~50-100mm) gratings for spectrometers and monochromators in medical instrumentation. This provided increased incentive for development of replication which continues (Stroke, 1967 p731; Loewen 1970; Palmer 1996).

2.2 Progress in Replicating Diffraction Gratings

Replication of gratings was investigated by Lord Rayleigh (1874) using classical silver-based photographic intensity techniques. However, being transmission amplitude gratings, their efficiencies were not competitive with prisms or ruled reflective gratings.

Wood (1944) demonstrated 'blazed' ruled vee-grooved reflective phase gratings with increased efficiency and showed that these could be replicated. The replica was made by pouring collodion onto the ruled master grating and, once hardened, the collodion layer was floated off and onto a blank substrate. Jarrell and Stroke (1964) recorded that shortcomings were encountered in maintaining an even layer thickness in and thence phase in the diffracted wavefront.

Wood then demonstrated concave gratings replicated from a steel master by a further process, due to White and Fraser (1949) of the Perkin-Elmer Co. and licensed to the Jarrell-Ash Company, Waltham, MA (Jarrell and Stroke 1964). This was similar to that developed for mirrors contemporarily (see Section 1.5). It commences with a layer of parting agent a few molecules thick, vapor-deposited onto the surface to be replicated [e.g. vacuum pump oil, "manitol" (Jarrell and Stroke 1964) or silicone fluid (Walker 1995)] followed by a ~1μm thick aluminium layer to take the (inverse) form of the master and become the surface of the new grating. Removed from the vacuum chamber, onto the newly deposited aluminium layer is spread a coating of epoxy resin and upon this is placed the blank as the replica substrate. The 'sandwich' is left to cure for 10-20 hours.

As in the case of mirrors, to maintain low distortion, the epoxy should be thin and of low-expansion with cure-time designed to minimize the effects of exothermic temperature rise. The figure of the replica blank should follow the master within a few visible fringes but a roughened surface is preferable for adhesion (see 1.2 for earlier consideration of the issues)

As to the size of 'phase-features' which may be reproduced, echelle gratings have been replicated with groove-densities of 30 grooves/mm and groove depths around 15μm, (i.e. comparable with width and depth limitations of the 'impressive' ruling process set by loading of the diamond ruling tool).

2.3 Grating Replication Methodology

With a single master ruled in steel, production and long-term viability were dependent on degradation with use and the ability to replace it. Wood's attempts to rule replacement steel masters were frustrated by damage to the diamond ruling tool from abrasive particles left embedded in the malleable steel substrate by the polishing process (Jarrell and Stroke 1964).

An alternative to steel masters was to replicate gratings ruled in vacuum coated aluminium films. As the master was then a coating, when problems of adhesion arose, the ruled master could be seriously damaged by parts of it adhering to the replica. Stroke (1967 pp731-3) gives some details of how the problem was circumnavigated. Working first with D K Rice at the Jarrell-Ash Company and later with PTR Optics of Waltham MA, (later becoming Optometrics Inc.), Sintiris (1972) developed techniques to enhance adhesion of metallic vacuum coatings to glass, to be ruled and used as masters. He reported 50 replicas deriving from one 7 1/4 inch (~180mm) master ruling and 120 from another (concave) master with up to 80-90% success rates (Stroke 1967 p731).

To preserve surface form in any orientation with respect to the gravity vector, a working rule for high quality mirrors is that the longest dimension (e.g. the diagonal of a rectangular blank) should ideally not exceed about six times the thickness. The location of the defined mounting support 'points' should be selected for defined minimum sag or slope as required. Such constraints on the thickness, volume and mass of the grating raises the need for replicating onto alternative lightened structures where needed.

2.4 Parting Replica from Master

Return on investment of effort depends on successful parting of the replica from a large ruling, particularly in the case of the first attempt. The process critically tests the scientific approach, diligence and care put into developing and testing parting-agents, adherent coatings and in their application in working techniques.

The surface of a blazed grating provides near-ideal adhesive 'keying' with a significant component of the grooves' steeper sides in shear during parting. Complete uniform coverage by the layer of parting agent is particularly important.

When parts of a replica coating adhere to a contiguous solid steel master, it is likely that only the (less-critical) replica coating will be seriously damaged so long as the replica fragments can be removed from the master. However, if instead the master surface is a coating, it also becomes vulnerable to lifting.

Substrates for gratings may be of usual materials used for comparable optical components such as mirrors including borosilicate crown glass, 'Pyrex', low expansion glassy/ceramic materials, including ultra-low expansion fused silica ('ULE'), 'Cervit' (formerly from the Owens company) and 'Zerodur' (from Schott). By choosing pairs of materials with dissimilar thermal expansion coefficients for respectively master and replica blanks, temperature cycling can be used to aid parting. Material costs of blanks bear some inverse relationship to thermal expansion so it is usual to invest in the lower expansion materials for masters and sub-masters.

2.5 Multiple Generation Replication

Once adhesion of the aluminium layer is assured, replicas can themselves be replicated. Indeed, in the case of plane gratings, it is prudent to use later generation replicas as sub-masters for production to minimize degradation of original rulings. Because the ruling process tends to better-define the groove bottom apex,

odd-numbered replica-generations tend to offer higher diffraction efficiency with well-defined exposed groove-tops.

After remaining essentially static for the first half of this century, over the next two decades, ruled grating widths increased progressively to 400mm and more for astronomy. Simultaneously, replicating from these provided for the increasing demand volume for the smaller gratings in viable numbers to satisfy intrument manufacture.

2.6 Replication of 'Holographic' Gratings

With the advent of high quality phase holograms made from photoresist developed for VLSI 'microchip' manufacture, the technique was adapted to record a straight parallel equispaced optical fringe pattern generated interferometrically by a pair of plane mirrors inclined to yield the required fringe spacing. Insofar as the grating is made from, and designed to generate, simple wavefront forms (plane or spherical), it does not possess three-dimensional image reconstruction capability and the term 'holographic grating' refers only to the shared photolithographic process adapted from VLSI manufacture.

The photoresist is spun onto the blank in an even layer, exposed to the appropriate optical fringe pattern and chemically developed to produce a grating with variations in depth and thence phase in the diffracted beam. Using only the basic fringe-pattern, a pseudo-sinusoidal groove-profile is obtained. Combined with one or more odd multifringe harmonics, grooves can be made with 'blazed' vee-form. Although it was expected that such gratings would be readily amenable to manufacture using the original 'holographic' (*Sic.*) techniques, replication is desirable for reasons of economy and quality-control. This was done in PTR/Optometrics labs using masters generated by Dr M Hutley of the UK National Physical Laboratory, Teddington, UK.

3 Concluding Comments

A great merit of replication is that, where a master can be produced, even at considerable effort, with surface finish, form and/or features (such as arise in diffraction-gratings, aspheric mirrors or 'cube-corner' optics), its characteristics can be replicated to produce a batch of such components to quality levels approaching that of the original.

Processes for replicating a surface to optical form and fine polish levels are much dependent on the use of proprietary techniques and understanding developed through commercial production requirements, which tend to be governed by need. However, by considering the breadth of available literature from a manufacturing engineering science viewpoint, a spread of problems has been raised of which account may be taken.

4 Acknowledgments

The authors acknowledge discussions on grating ruling with G R Harrison, sometime Dean of Sciences at the Massachusetts Institute of Technology and on replication with G Sintiris, founding Vice-President, PTR Optics Inc. and Consultant, Optometrics Inc.

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A Precision Polymer Injection Molding Process Assisted by Infrared Radiation to Upgrade Both Optical Quality and Transcribability

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1. Introduction

Injection molding of polymers is currently utilized in numerous industrial applications because of high productivity and repeatable quality of the molded products. In a typical injection molding process, resin material is melted in a heating barrel to a specified high temperature by electric heaters so as to become a viscoelastic fluid. The molten polymer is then injected with a high flow rate under ahigh pressure into a mold cavity of which the temperature is usually maintained between 300 and 370 K. During the filling stage the polymer melt is cooled by its surface in contact with the cold mold wall, and a "solidified surface layer" is formed in the vicinity of the mold wall as shown in Fig.1. Because of the high viscosity in this layer, injection molded polymer products inherently suffer many different problems such as shape deformation, residual stresses, low moldability, ill transcription and birefringence. These problems are fatal defects for precision components such as photo memory disks, camera lenses, electronic devices and micro-machine components[1,2].

To avoid these problems, the authors [3,4,5] have proposed an "Injection Molding Process Assisted by Radiation Heating", developed from the heat transfer point of view. In the proposed injection molding process, the temperature of the molded polymer near the contact surface is kept high by infrared (IR) radiation heating. Besides the mold wall transparent to IR is not heated directly by irradiation and continuously cools the polymer during the filling and cooling stages of process. Consequently, the temperature of the molded polymer decreases rapidly when the radiation heating is stopped. The elongation of the cycle time due to the radiation heating is therefore very small.

In order to realize the cooling control due to the proposed concept, the authors used a CO_2 laser as a radiation heating source, and Zinc Selenide (ZnSe) as a transparent window material for the radiation. ZnSe is almost completely transparent to a CO_2 laser beam (wave length = 10.6 μm). On the other hand, most polymers are semi-transparent to the IR radiation. For example, the absorptivity of polystyrene for CO_2 laser irradiation is about 3000 times higher than that of ZnSe. Consequently, the CO_2 laser irradiation only heats the polymer melt near the contact surface and suppresses generation of the solidified layer in the cavity having a ZnSe window as shown in Fig. 2.

In this paper the feasibility of the proposed process was investigated experimentally. Experiments focused on reduction of the birefringence frozen in the skin layer and improvement of the transcription of microscale configuration on the mold surface onto the molded polymer surface.

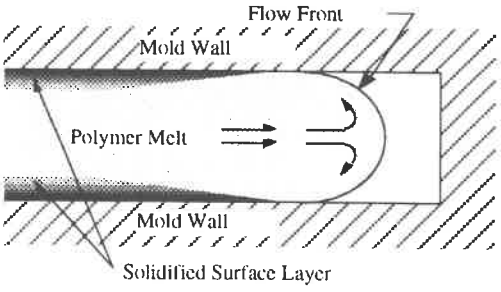


Fig.1 polymer melt in a cavity in a conventional molding process

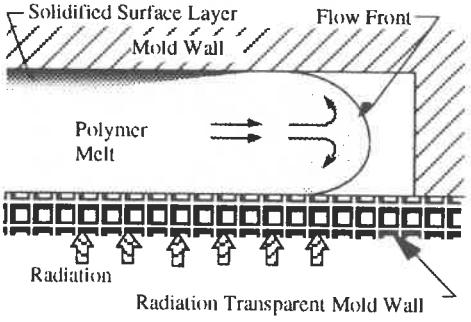


Fig.2 Polymer melt behavior in acavity in the molding process assisted by radiation heating

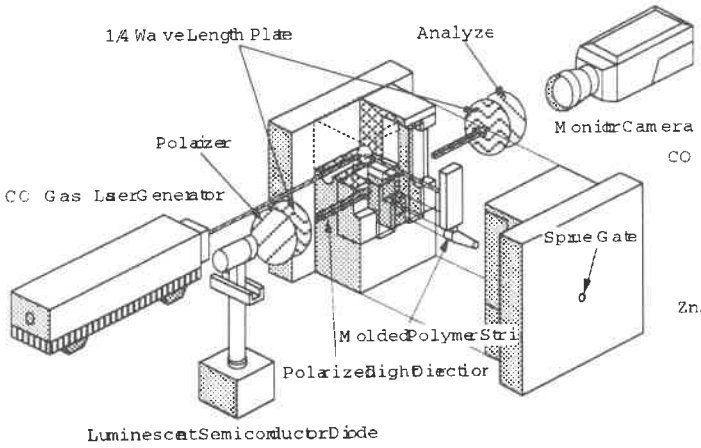


Fig. 3. Experimental Setup

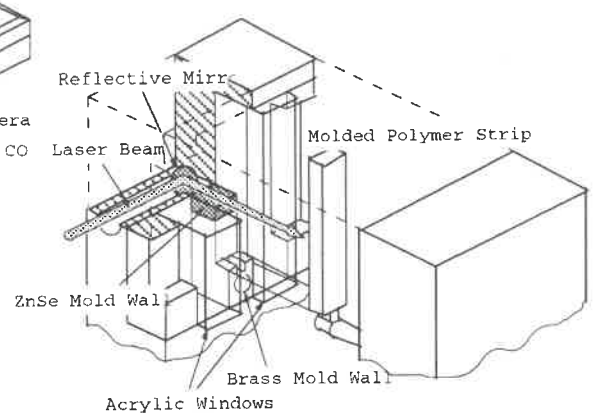


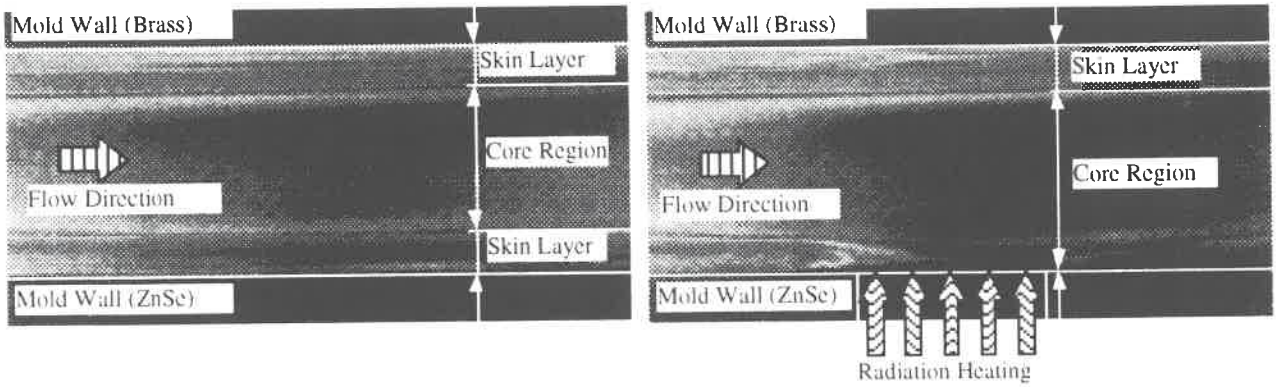
Fig.4. Detail of the mold asssisted by irradiation

2. Experimental Setup

A schematic of the experimental setup is shown in Fig. 3. It consisted of two optical systems, one for heating, and another for observation of the birefringence distributions. A CO_2 laser was used as the IR radiation heating source. The laser beam was reflected by a metal mirror installed in the mold, and then radiated the polymer melt inside the mold cavity as shown in Fig.4. The irradiated region of the polymer surface was limited to the circular area of the laser beam diameter (4 mmϕ).The mold walls consisted of a brass, and another mold wall had a ZnSe window transparent for the IR radiation. The other two side walls were fabricated from acrylic resin plates in order to observe the flow and the birefringence behavior of polymer melt. The time-dependent birefringence pattern was observed and recorded by a video camera.The sizes and shapes of the molded components are shown in Figs.6(a) and 8(a). The reduction of residual birefringence and the improvement of the transcribability due to IR irradiation were were examined.

3. Reduction of the Birefringence in the Molded Polymer

Molecular orientation is inherent in injection molded polymer components, since the polymer molecules near the mold wall are stretched by the polymer flow during the filling stage, and are frozen in this stretched condition by rapid cooling through contact surface in the cold mold wall. The birefringence due to the molecular orientation seriously affects the optical quality of injection molded such as CD-ROMs, mirrors and lenses[1-8]. Figure 5 shows typical birefringence patterns in the entirely solidified polymer in the mold cavity, both without and with IR radiation heating. As shown in Fig. 5(a), a large number of fringes exist near the surface of the molded polymer. These fringes correspond to the iso-birefringence lines, and this means that the polymer molecules are highly oriented in this region. As shown in Fig. 5(b), however, the highly oriented layer, i.e. the "solidified surface layer," disappears in the vicinity of the surface in the irradiated region, and the birefringence is effectively reduced. Figure 7 shows the birefringence distributions measured by a polarizing microscope on a specimen cut out from an irradiated polymer strip as shown in Fig. 6. Figure 7 shows the magnitude of birefringence in the x-y plane. The left end of the figure corresponds to the irradiated surface of the molded polymer. As shown in Fig. 7(a), birefringence obviously appears near both surfaces at the location which received no irradiation at the location A in Fig. 6(a), and this birefringence corresponds to the solidified surface layer. On the other hand, as shown in Fig.7 (b), the residual birefringence on the irradiated surface which was measured at the location B in Fig. 6(b) was effectively reduced by the CO_2 laser heating.



(a) No radiation heating

(b) Radiation heating assisted

Fig.5. Birefringence patterns with in the molded polymer strips

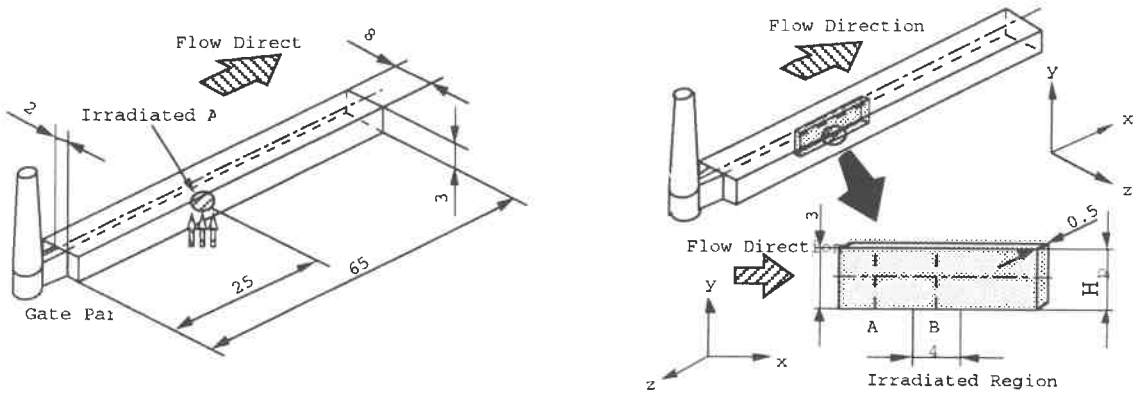
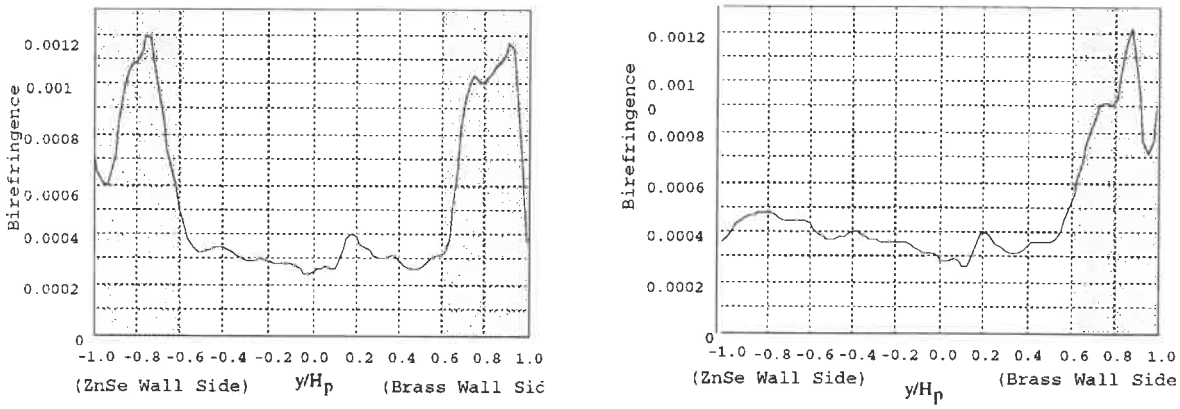


Fig.6. A molded strip to observe the resiual birefringence

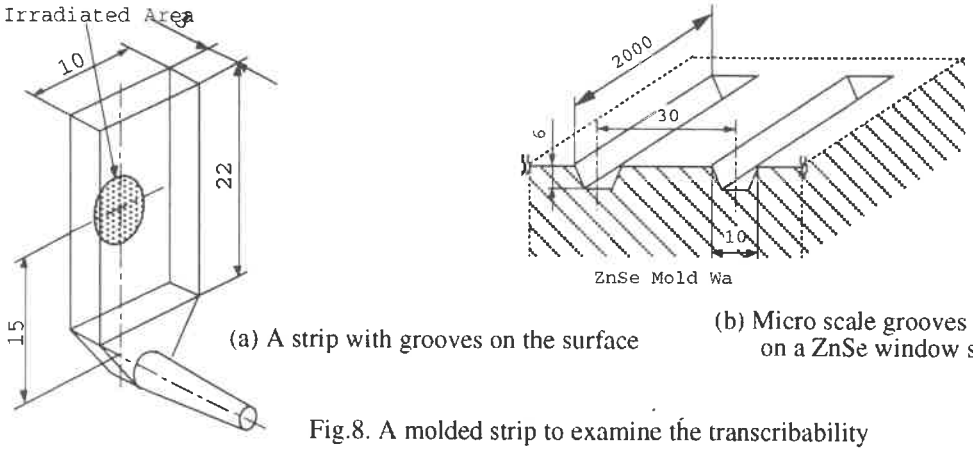


(a) Noradiation heating (b) Radiation Assisted

Fig.7. Residual birefringence in the gapwise direction

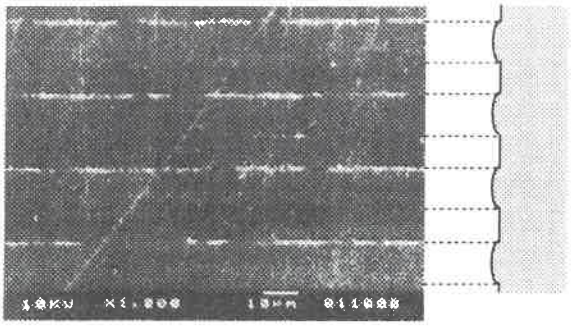
4. Improvement of Transcribability of the Molded Polymer Surface

Good surface transcription is very important for optical and photo-electronic components. It is however very difficult to manufacture these highly precise polymer devices through the conventional injection molding process. Specifically, the generation of the solidified surface layer degrades the transcribability on polymer surface. In this study, the ZnSe wall having microscale grooves on its surface is used to examine the transcribability. Figure 9 shows the SEM photographs of replication of the grooves on the polymer surface. Figures 9(a) and (b) show the polymer surface molded without and with IR radiation, respectively. The transcribability of the molded polymer surface was obviously improved by applying the radiation heating. The height of the protrusions on the polymer surface were measured for various mold wall temperatures and injection rates. As shown in Fig.10, the transcribability of the molded polymer surface is not unfavorable without irradiation, even when the mold wall is heated up to 340K. On the contrary, the protrusion height is effectively increased when the radiation heating is applied.

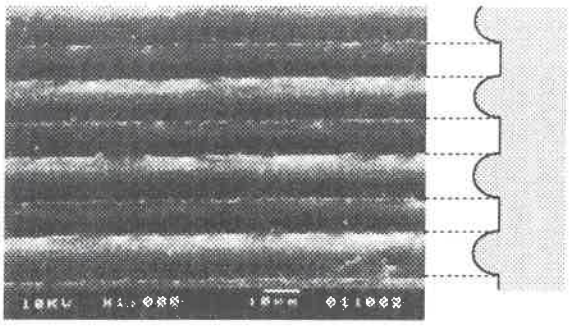


(a) A strip with grooves on the surface (b) Micro scale grooves engraved on a ZnSe window surface (μm)

Fig.8. A molded strip to examine the transcribability



(a) No radiation heating



(b) Radiation assisted

Fig.9. SEM of micro scale protrusions on the molded surface due to transcription

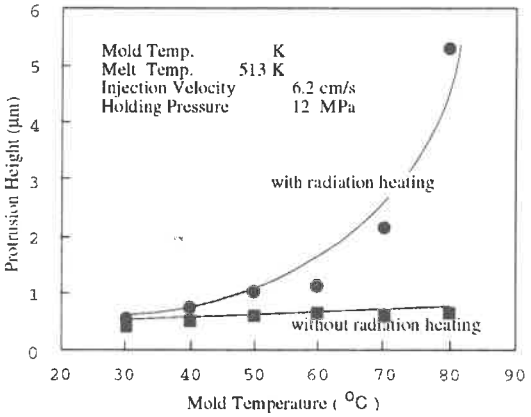


Fig.10. Influence of mold wall temperature on transcribability

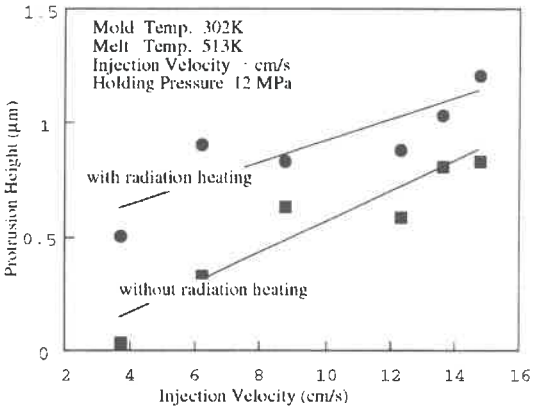


Fig.11. Influence of injection velocity on transcribability

5. Conclusion

An innovative injection molding process assisted by IR radiation heating to improve the optical quality and transcribability is proposed. The effectiveness of assistance of radiation heating associated with injection molded polymer components was experimentally confirmed for two major issues, namely: the residual birefringence in the skin layer as well as the transcribability of the molded surface for microscale geometries. Although the proposed process requires an IR radiation heat source and a mold wall material transparent to IR radiation, it is sure to be practically feasible for improving the quality of high precision polymer components having micro scale configurations because this process hardly affects the process time required for the molding.

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Injection Molding for Micro-Structure of Optical Elements using Mold-Core Extrusion

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1. Introduction

Mass production of optical elements requires an inexpensive reproduction process. In optical industry, the injection molding of a transparent plastic material is the most popular process. But the optical element needs a fine reproduction process with precision of about $\lambda/10$ (0.06 μm).

The fine reproduction is realized by the perfect contact between a mold surface and a solidified plastic skin during the whole injection time. As the plastic material has about 1 % volume shrinkage after solidification, the plastic's pressure in a cavity reduces gradually and reaches to zero. It means that a spacing gap happens between the mold and the skin.

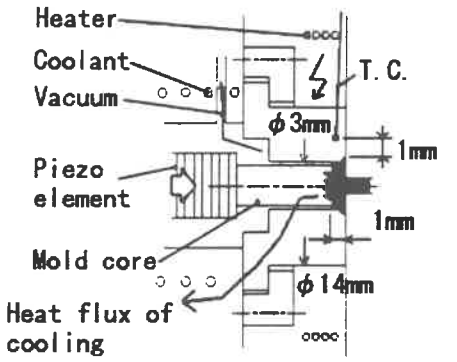
To keep high pressure in the cavity, the industry employs a secondary pressure peak at the middle stage of injection time. For example, a compact disk production increases a clamping force of the molds after injection. An optical lens production pushes the skin after injection using an extrusion pin which extrudes an injected product after opening the molds. However, the above-mentioned production with the $\lambda/10$ precision is still very difficult because the secondary pressure is not distributed uniformly.

The authors introduce a new process, extruding a mold-core at the middle stage of injection time. On the surface of the mold-core, we fabricate a functional micro-structure. For example, triangular grooves of 1μm in depth and 1.5 μm in width are on the surface. We put a force sensor to measure the pressure working on the mold surface, and control the pressure as a piezo element precisely moves the mold-core. We use a homemade miniature injection machine using a miniature mold (ϕ14 mm, its clamping pressure is 130 MPa) , and a purchased small injection machine (FANUC α15C, its clamping force is 150 kN). Each machine has the mold-core extrusion mechanism in the mold.

2. Experimental method

Using the homemade miniature injection machine (Fig. 1), we reproduced the triangular grooves at the following condition: controlled injection pressure during injection time is about 15-20 MPa, mold-core (Fig. 3) movement is 10 μm, injected plastic is poly-styrene, injected plastic temperature is 275 ℃, mold temperature is 135 ℃, mold material is Inver, and initial cavity pressure is 1 MPa (0.1 atm. in vacuum). When the cavity pressure rises around 20 MPa, we move the mold-core by the piezo element to prevent from the spacing gap between mold-core and the skin. Triangular grooves on the mold-core (Fig. 2) on the mold is cut by a mold cutting machine designed by us [1].

Using the purchased small injection machine, we are now developing a mold-core mechanism using a piezo element and force sensor (Kistler, ActoSens). The triangular grooves were cut by a fine milling machine (FANUC, ROBOnano Ui) [2].



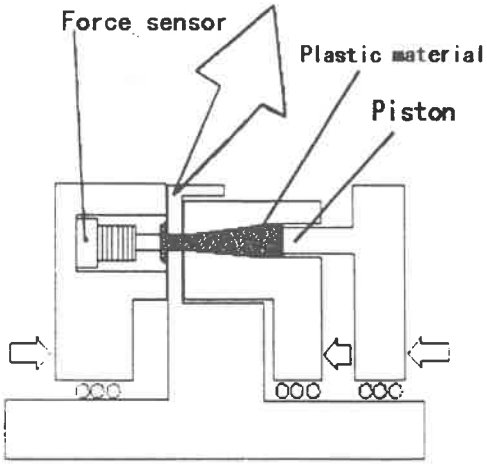


Fig. 1 Schematic view of the home made miniature injection machine

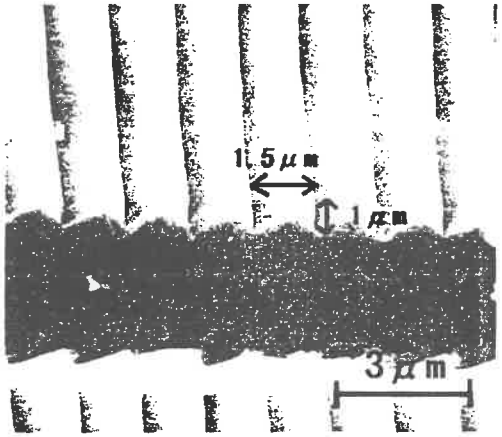


Fig. 2 Triangular grooves on the mold-core

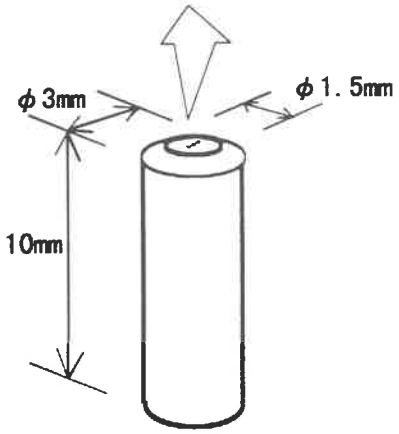


Fig. 3 Schematic view of mold-core of the homemade miniature injection machine

3. Results

We reproduced the triangular grooves by controling the cavity pressure. When the cavity pressure rised around 20 MPa, we extruded the mold-core (Fig .4). The piezo element was impressed to about 145 V: the piezo element moves under no load about 12.2 μm at 145 V. When the mold temperature is lower than 135 ℃, mold-core extrusion deforms the grooves, because the half solidified skin is already too hard.

We injected it without mold-core extrusion as a reference (Fig. 5). After a piston stops to inject, the pressure decreases. The reduction rate is 8 MPa / 20 sec without extrusion, but 12 MPa / 20 sec with extrusion. The extrusion could make a good contact for cooling.

Without extruding the mold-core, we can not reproduce sufficient triangular grooves with a sharp ridge and valley. Fig. 7 shows the round ridge. We can see the more sharp ridge and valley in Fig. 6. However, the figure shows some wave patterns of the plastic material at the end of the triangular grooves (pointed by an arrow in Fig. 6) . We never see the wave pattern without any extrusion. The wave pattern looks the deformation of the surface.

4. Discussion

The industry suggested that the solidified skin should not be deformed in order to work high optical performance ; the wave pattern as shown in Fig. 6 is not acceptable; we should extrude the flexible, lequid-phase plastic material just after injection. We have studied an optimum gate feature for injection molds using a heat flux sensor illustrated in Fig. 8. Two thermal couples are located at two different points – 0.3 mm deep and 0.6 mm deep from the surface – to calculate heat flux. The sensor could detect a gate sealing because heat flux is reduced after solidification. However, this experiment does not prepare any gate (Fig. 1); the spacing gap becomes larger ; the piezo element needs larger extrusion. We will be able to find the best extrusion time with a gate design and with skin hardness detection using the heat flux sensor.

The mold-core extrusion is required to move straight. But the experiment dose not design any guide for straight movement. The mold-core was sometimes slipped up to several 4 μm when the skin hardness was not uniformed. A new mold for the purchased small injectionmachine should be improved by a new mechanism to prevent the mold-core from twisting, rotating or bending.

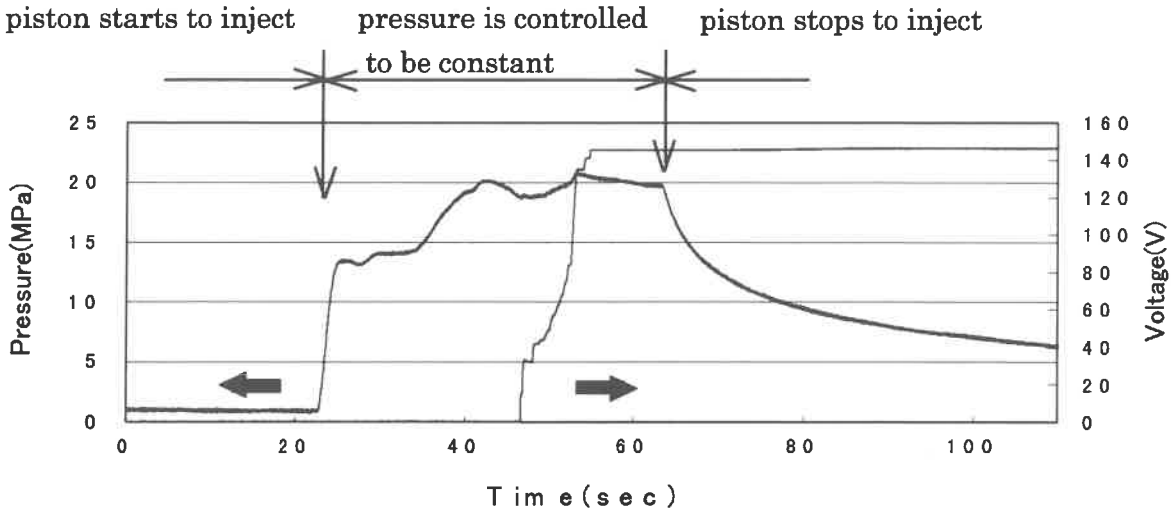


Fig. 4 Cavity pressure and piezo element impressed voltage with mold-core extrusion

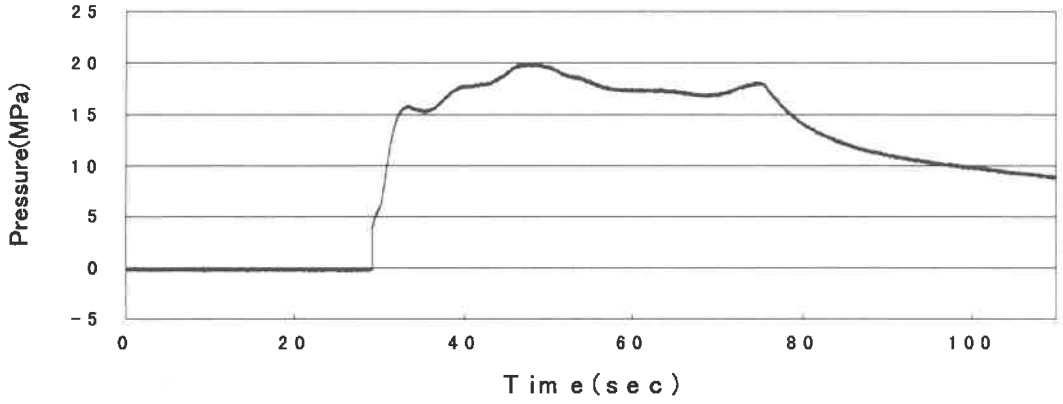


Fig. 5 Cavity pressure without extrusion

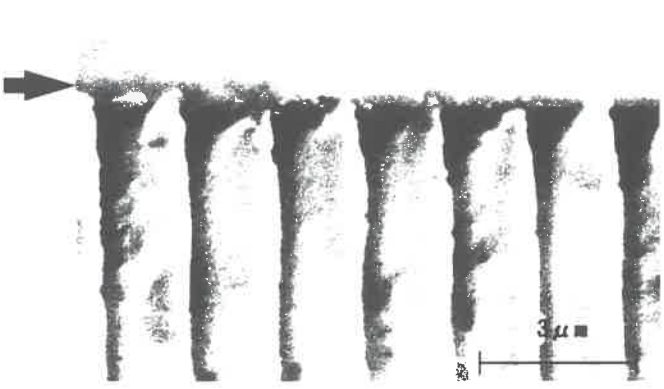


Fig. 6 SEM view of injected triangular grooves with mold-core extrusion

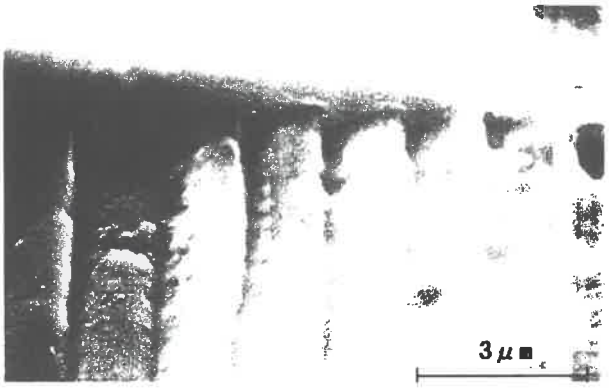


Fig. 7 SEM view of injected triangular grooves without any extrusion

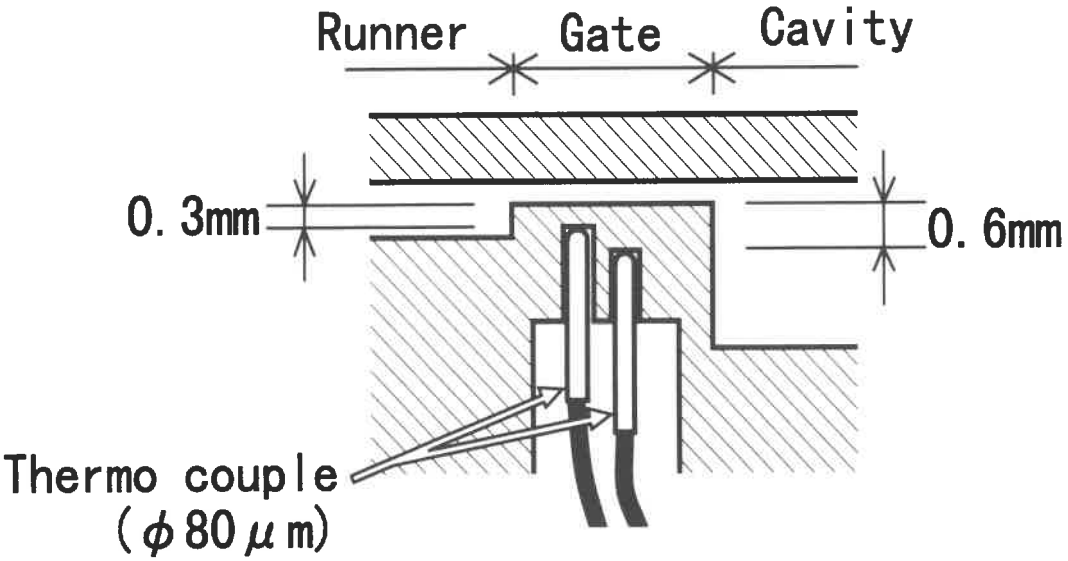


Fig. 8 Heat flux sensor

5. Conclusion

We succeeded in producing the triangular grooves of 1 μm in depth and 1.5 μm in width more precisely by using mold-core extruding process. To reproduce them without any deformation of the early solidified plastic film(the skin) , further design improvement is necessary for a gate feature, heat flux sensing or mold-core straight movement. Though the trial is still on the early-stage, we revealed that the precise extrusion of the mold-core is effective for micro-structure reproduction.

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REPLICATION - FROM MACRO TO MICRO TO NANO...

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Optics manufacture has always involved replication. The simplest optic is formed by replicating a radius into a piece of glass and then progressively removing the generating damage while keeping the replication of the curve intact or making it better match the desired form. This report outlines some of the optical replication challenges on the spectrum of parts from 5.0 meter down to nanometer structures used on today's precision optical surfaces.

MACRO

Starting at the large end, optical structures are used to make collimating lenses for large format projection display. In particular, 5.0 meter fresnel lenses are replicated by machining a reverse fresnel structure into a diamond-machinable substrate and using this as a mold to cast acrylic fresnel lenses (see figure 1). Typical pitch for the fresnel facets on this size optic is 0.25 mm resulting in 10,000 individual concentric facets with a different angle to each facet. One begins to get a feel for the challenges both in the manufacture of the mold (machinery size, stiffness and stability, uniform surface finish, correct angle on each facet, diamond tool wear control, control of the miles and miles of chips formed by the process, substrate selection and purity to mention a few of the variables) and the casting process itself (from mold design, chemical formulation for homogeneous product and optical performance, cure process control, part release and removal from the mold, and testing of the optic).

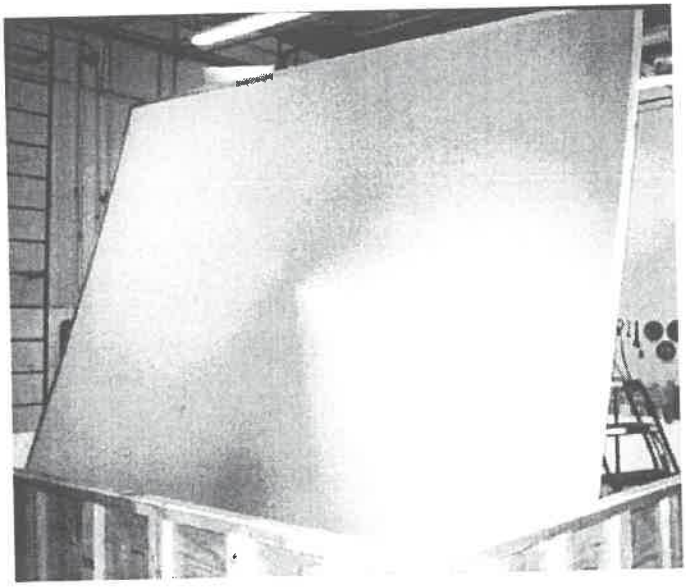


Figure 1 - 4.7 meter fresnel lens mold

The final acrylic sheet with the optical microstructure cast into it is approximately 9 mm thick and weighs 126 kilogram. This gives a product with an aspect ratio of 556/1 (5 meter diameter / 9 mm thick). In stark contrast, an acrylic lens to perform this same function (back focal length of 3.0 meter) without the fresnel structure would be 1.6 meters thick and weigh 13,330 kilogram! The advantages of the fresnel microstructure become evident.

Handling issues for this large fresnel lens become an engineering challenge as both sides of the optic have optical surfaces where the surface finish must be preserved. The fidelity of the microstructure must also be preserved in the replication process for the optic to function properly. To date, casting is the only process to yield the required fidelity on optics this size.

NANO

At the other end of the spectrum are structures that are being used to replace multilayer antireflective (AR) coatings on polymer optic. The eye of the moth is formed with a series of regular "columns" that have a spacing and height below the wavelength of light (see figure 2). This structure acts as a graded index surface dividing the light waves at sub-wavelength intervals so that the index change from air into the material is not as prevalent as with 'smooth' surfaces: thus light is transmitted into the eye rather than reflected.

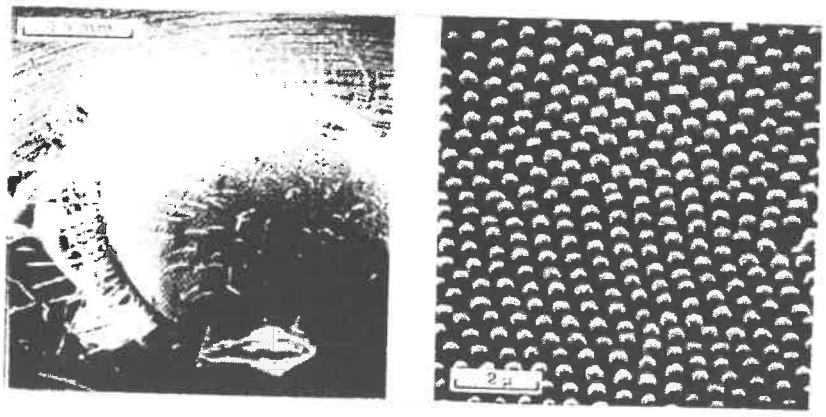
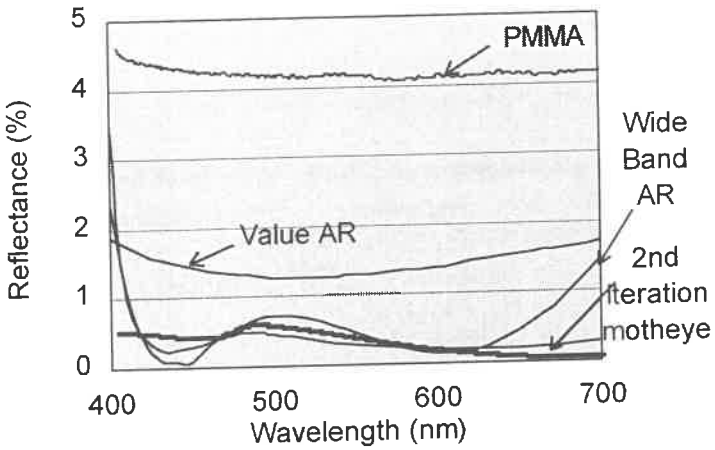


Figure 2 - SEM of actual moth eye

With the advent of submicron photolithographic techniques, it is possible to manufacture posts with spacing and height of approximately 0.25 micron. An area full of this 'motheye' structure functions similar to a wide band AR coating. The motheye surface has been shown to outperform AR coatings at non-normal incidence angles.

The challenges of the motheye structure are as diverse as the large fresnel. The ability to manufacture the master with uniform height and spacing over large areas requires control of variables such as photoresist thickness and purity, photolithographic processes for making the structures such as large area exposure and development techniques, and novel processes such as holographic photolithography, multi-beam interference lithography, and relatively large area masking techniques.

The motheye structure performs antireflection by breaking up impinging light due to the structure being smaller than the wavelength of light (see figure 3 which compares the motheye



structure to 'Value' single layer AR coating and multilayer coatings). Thus, normal metrology instruments such as microscopy and white light interferometry will not resolve the structure. This creates metrology challenges because the structure must be SEM or AFM inspected. These tools are relatively small area inspection devices thus making the overall quality of the master or optic difficult to quantify.

Figure 3 - Comparison of 'Motheye' to AR coatings

To replicate this nanostructure into a polymer requires close control over the replication techniques. With electroforming processes such as those used for manufacture of compact discs (CD's) one of the unknowns for feature fidelity is the grain size of the nickel that is grown as the mother or the stamper. Given that the motheye structure has been replicated down several generations with satisfactory performance, the grain size of the process must be much less than the 0.25 micron motheye pitch and structure height size. Figure 4 shows the motheye structure in acrylic. This is an early forth generation replica where deformations are evident but performance is not affected.

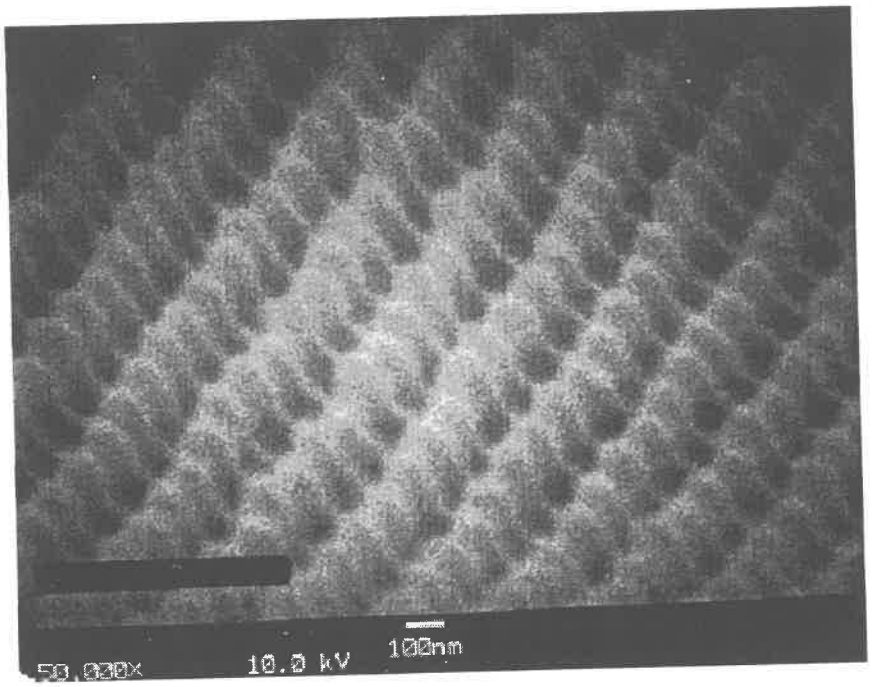


Figure 4 - Forth generation SEM of 'Motheye' in acrylic
courtesy of Holographic Lithography Systems - Bedford, MA

REPLICATION VARIABLES

With the above in mind, several variables emerge that can be applied to all optical replication.

Aspect ratio: the ratio of the optic's diameter to its center thickness. In macroreplication, conventional rules for aspect ratio loose their value. In nanoreplication, even the smallest structures made to date exhibit replication problems if structure aspect ratios are too high: replication becomes difficult and damage and/or incomplete replication results.

Draft: angle of surface from vertical necessary for replication. Whether parts are to be removed from a mold or replications are to be removed from masters, draft angles are required. In some cases, separation deformations can negate draft angles: bending of the form or the mandrel can "lock" the structure. For most optical structures, minimal draft is necessary for performance but manufacturers like maximum draft for production.

Surface finish: microstructure (or nanostructure) that affects replication. At times, surface finishes are produced that, on their scale, cause replication difficulties. For instance, a diffuse surface that has pockets or holes that create 'negative' draft or relatively large aspect ratios can induce locking of the part or lower generation replications. Due to the sub-microscopic nature of these defects, they can be very hard to identify and sometimes impossible to alleviate.

Method of replication: several common methods of optical replication into polymer and relative characteristics are:

	Casting	UV Cure	Compression Molding	Injection Molding	Compression/ Injection
Cycle time	High	Medium	High	Short	Medium
Stress - birefringence	Low	Medium	Low	High	Low
Fidelity	High	Medium	High	Low	High
Cost - relative	High	Medium	Medium	Low	Medium

These are generalities, have exceptions due to engineering excellence, but for the majority of production hold relative and can be used as a guide for replication.

As we move to the future, the size of optic will push the limits as we know them. We will be producing and replicating greater than 5 meter optic with microstructures structures less than 100 nanometer in size. This variation of scale combined with the mastering and replication difficulties will continue to keep the challenges high for the manufacturer and increase the benefits of these optic for the end user.

For presentation at the American Society of Precision Engineering Spring Topical Meeting 'Precision Fabrication and Replication' April 14-15, 1999

REMOVAL OF FORM ERROR IN REPLICATED OPTICS

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Abstract

A technique for reducing form errors in molded optics is described and tested. A thin film of U V Cure epoxy is cast on a surface with a large form error with a diamond-turned surface serving as the mold. Form error reductions are at least five-fold. Distortion due to thin film stresses are modeled and compensated for to give more than an order of magnitude of form error reduction.

Motivation

Precision molded optics have come a long way in the past decade, lowering cost and increasing precision to where sub-micron sized features are routinely reproduced for compact discs. New processes and new applications for established technologies such as injection-compression molding and vacuum embossing[1] have extended the capabilities of replicated optics and opened up new markets that would simply not be feasible without the low cost and durability associated with replicated optics. While the main thrust has been to improve fidelity, form errors on even the best injection-molded optics continue to be large (CD's tend to have a form error around 50 μm). Injection molding[2] is currently the most popular choice for replicating optics due mainly to high throughput and an established support industry. Certain demanding applications do exist, however, where the disadvantages of injection molding become apparent. Birefringence introduced by differential shrinkage and the "frozen layer" [3] formed on mold cavity walls is an indicator of internal stresses that distort the part as it cools. Improved process control can do much to reduce figure error[4], but still does not put precision molded optics on par with quality ground imaging optics. Other novel schemes, such as reducing the bulk of the optic[5] or RF curing of thermoset polymers[6] have been tried with some success, but the goal of inexpensive replicated optics for use in demanding areas such as SLR camera lenses and laser optics remains a major challenge in replication.

Form Error Correction Technique

To remove figure error from molded glass or plastic optics, the technique illustrated in Figure 1 is used. The molded substrate made of glass or plastic can be injection molded with typical form errors of 50 to 100 μm over 100 mm. A mold that has been diamond turned or precision ground and polished is then used to contain a thin film (~100 μm) of U V Cure epoxy (Summer Laboratories J-91 in the described experiments) between itself and the substrate. The epoxy can then be cured through the transparent substrate. When the mold is removed, the epoxy film remains on the substrate and presents a surface that accurately mirrors that of the mold. The effect of slight dimensional changes in the epoxy film upon curing will be minimized by the fact that the film is relatively thin. As long as the substrate remains substantially stiffer than the film, little distortion will occur due to surface stresses.

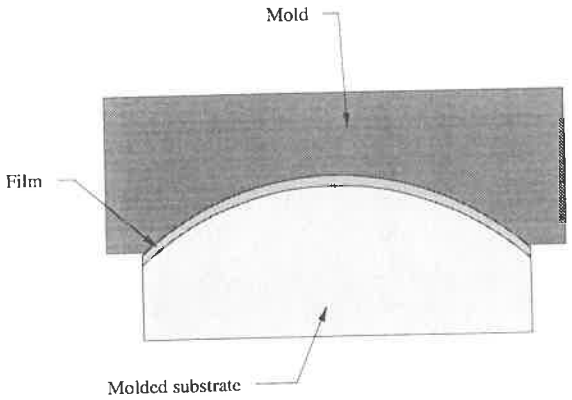

Figure 1. *The substrate is a molded plastic or glass part with an unacceptably large form error. A thin film of Epoxy is cast between the mold and the substrate. What remains on the substrate will be an epoxy surface that precisely replicates the form of the mold.*

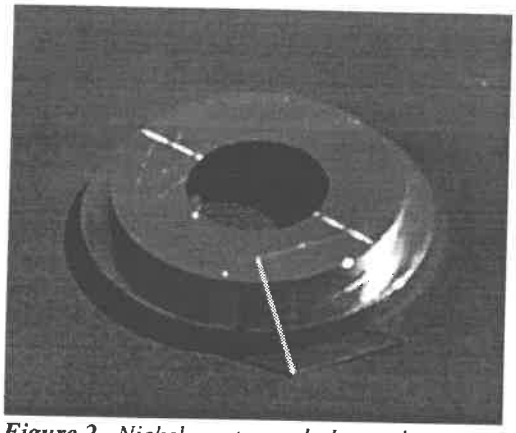

Figure 2. *Nickel master and glass substrate used in first experiments*

First Molding Experiments

The setup used in the first set of experiments is shown in Figure 2. A 25mm square glass slide, 1 mm thick, was used as a substrate and a diamond turned nickel annulus with an outside diameter of 75mm was used as a mold. The film thickness for the epoxy cast between the two was between 50 and 150 μm.

Roughness

The features left by a diamond tool on a surface tend to be in the sub-micrometer range in the vertical direction and thus make a reasonable test for fidelity. Figure 3 shows cross-sections of both the nickel master's and the molded part's surface. The reproduction of the smallest of surface features (<10 nm) appears to be excellent.

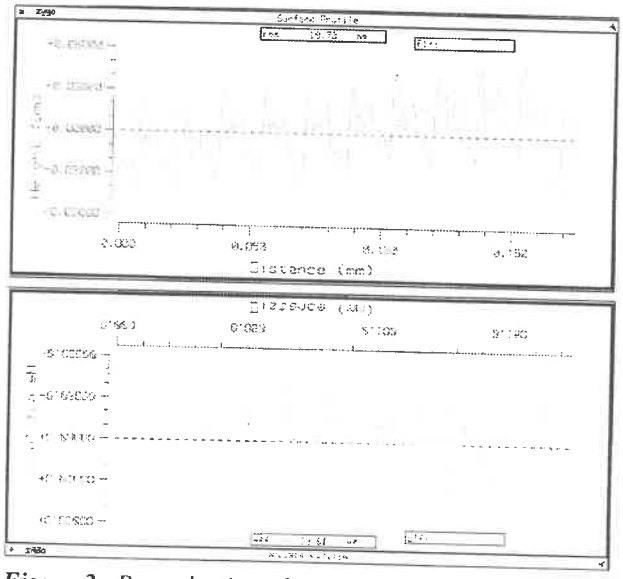

Figure 3. *Reproduction of regular features left by a diamond tool as small as 10 nm is excellent.*

Correcting for Form Error

The results of form error measurements of the glass substrate, the nickel mold, and the epoxy surface are shown in Figures 4, 5, and 6 respectively. There was a significant improvement in the figure of the cast part and excellent reproduction of the surface form of the mold, resulting in the removal of an appreciable form error from the slide surface. Due to the close index matching between the glass slide and the epoxy, (1.49 and 1.55 respectively), fresnel reflection losses are low (.04% near normal incidence) and the desired optical effects associated with a surface that is true to form are achieved.

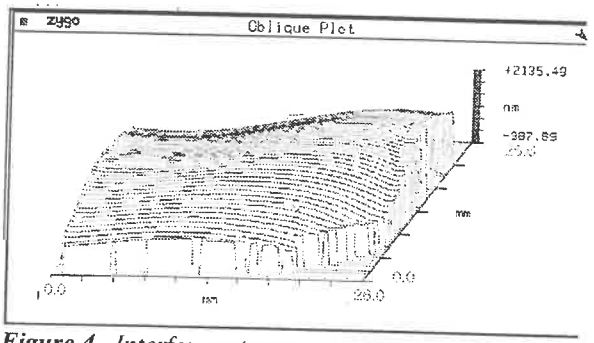

Figure 4. *Interferometer measurement of glass slide before casting(P-V=4.936 wave).*

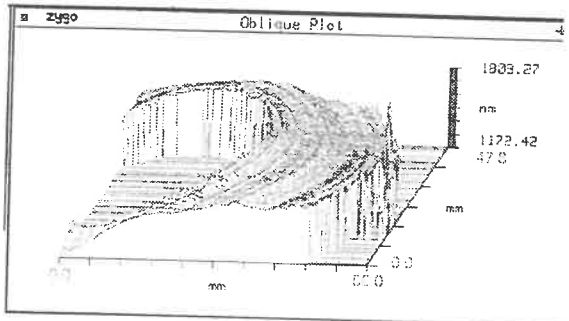

Figure 5. *Interferometer measurement of Nickel master before casting (P-V=1.006 wave).*

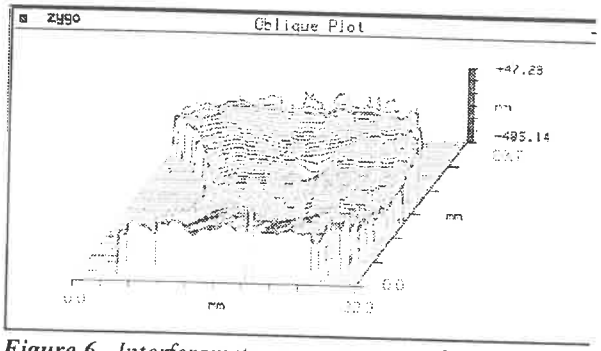

Figure 6. *Interferometer measurement of epoxy surface cast on glass slide(P-V=0.841 wave).*

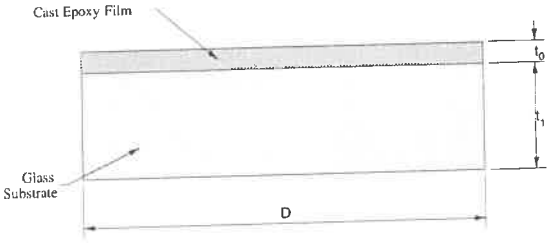

Figure 7. *A cast epoxy film of thickness t_0 on a glass substrate of thickness t_1 will distort the substrate due to stresses resulting from cure shrinkage.*

The slight difference in surface finish of the nickel master and the cast part is, in large part due to the difference in the area measured.

Surface Stress

For relatively small areas in relation to the thickness and stiffness of the substrate, the scheme for correcting for form error with a thin epoxy film works quite well. If, however, the substrate is thin enough, flexible enough or lacks stiffness, the surface tension caused by the shrinkage of the epoxy will distort the part and possibly negate any gains error correction made by the process. In order to accommodate this distortion, a simple model[7] is used to approximate the radius of curvature of a finished part based on the thickness t_0 and the modulus E_0 of the cast epoxy film, the thickness t_1 and the modulus E_0 of the substrate. The stress in the epoxy film σ_f is assumed to be the shrinkage of the material upon cure and can thus be used to evaluate the line tension λ in the film via

$$\lambda = \sigma_f E_0 t_0 . \qquad (1)$$

Thus, with Poisson's ratio μ (assumed to be .3 for most materials), the radius of curvature of the epoxy/substrate sandwich,

$$R = \frac{E_1 t_1^2}{6\lambda(1-\mu)} . \qquad (2)$$

When expressions (1) and (2) are used to evaluate the radius for an epoxy/glass sandwich (E_0=1.2 GPa, E_1=60 GPa), as shown in Figure 7, where the film thickness t_0 is 100 µm and the glass substrate t_1 is 3 mm, the radius of curvature is about 250m. Over a distance of 25 mm (the size of the first test parts), this translates to a sag of 580 nm. If, however, the part size increases to 100 mm, the sag becomes 10 µm. Such a large form error can be a problem in imaging optics, so it would be desirable to at least reduce it substantially if not remove it entirely. One way to remove this form error is to machine the mold with a form that accounts for the deflection of the final part. Ostensibly, the first-order approximation discussed above using the line tension λ determines the amount of deviation required in the mold.

Molding a Large Flat

A second set of molding experiments was devised to verify that the form error due to distortion of the substrate as a result of epoxy cure shrinkage could, in

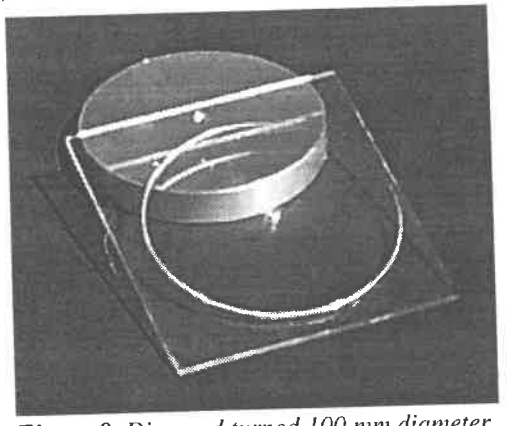

Figure 8. *Diamond turned 100 nm diameter master with glass slide and epoxy cast.*

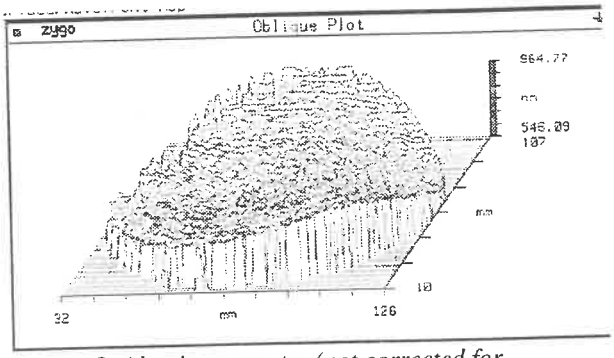

Figure 9. *Aluminum master (not corrected for distortion). P-V = .66 wave.*

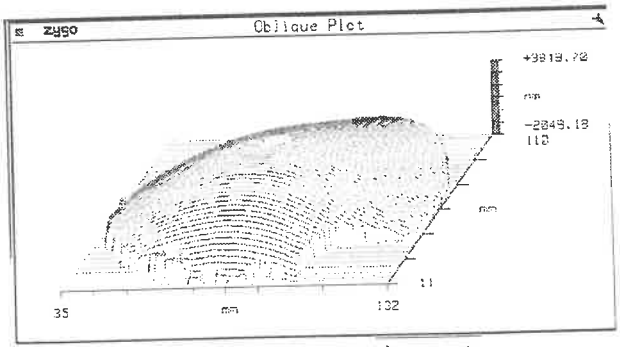

Figure 10. *Epoxy on 3mm glass substrate (not corrected for distortion). P-V = 9.3 wave.*

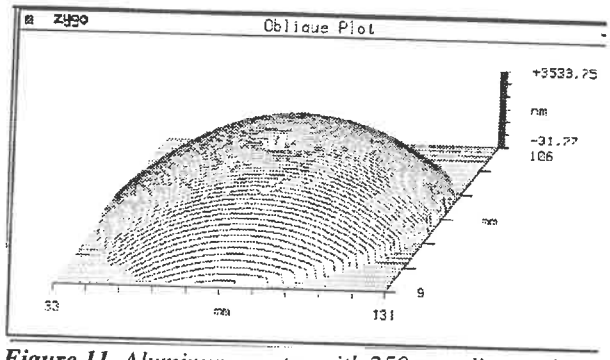

Figure 11. *Aluminum master with 250 m radius surface (corrected for distortion). P-V = 5.2 wave.*

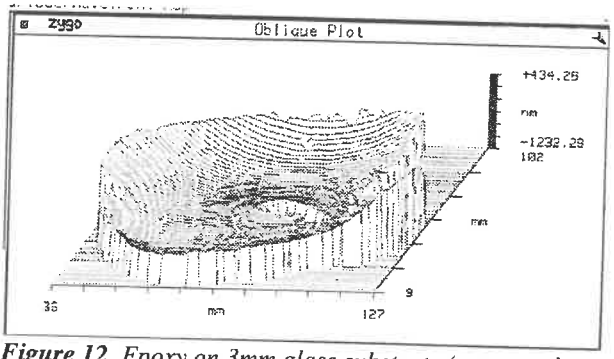

Figure 12. *Epoxy on 3mm glass substrate (corrected for distortion). P-V = 2.6 wave.*

fact, be corrected for. The substrates were, once again, glass with the mold being a diamond turned 100 mm diameter aluminum flat as shown in Figure 8. A hole in the center of the mold facilitated part removal since no mold release agents were used for fear of their influence on the experiments. Several parts were cast on the flat and measured on a Zygo GPI XP interferometer. The mold was then diamond turned again with a radius in the inverse of what the form error on the part was. Several parts were, again, cast and measured on the interferometer.

Correcting for Distortion

Figures 9, 10, 11, and 12 show the course of the molding experiments to remove form error in a large part due to tension in the thin film of epoxy. The first sample was cast between a flat (PV=.4 µm=.66 wave) aluminum mold shown in Figure 9 and an ordinary plate glass slide (PV>20µm or 35 wave). The epoxy remained on the glass after mold separation and the irregular distortion in the glass surface was removed as observed in previous experiments. There was, however, convex distortion in the surface with a radius of about 360 m and a sag of 9.3 wave (see Figure 10). This convex distortion is unusual in that it means the epoxy actually expanded upon cure - possibly a result of the curing conditions. The expansion was verified in several other experiments and shown to be a consistent 0.3%. Accepting this relatively unusual condition (it was repeatable, after all), the master was machined with a 250 m radius convex surface shown in Figure 11. Another part was then cast under identical conditions as the previous one resulting in a surface with 2.6 wave of surface distortion - a factor of four improvement. The corrected part, shown in Figure 12, retains some distortion at the edges. This is probably due to the fact that the distortion is not purely spherical. If this final amount of error is to be predicted, a more complex model will have to be developed to account for higher order distortions.

Conclusions

The described replication method for improving molded optics shows promise in three areas:

1. Small, albeit low aspect ratio, features to 10 nm are reproduced well in the UV cure epoxy used.
2. A substantial amount of form error can be removed from a substrate.
3. For thin or compliant substrates, distortion caused by cure shrinkage can be compensated for using a simple line tension model.

Experiments with PMMA substrates were largely unsuccessful because of poor bonding between PMMA and the epoxy as well as difficulty in curing the epoxy through the plastic material since most commercial grades of PMMA are treated with a UV absorber. Additional refinements to the distortion model as well as better control over film thickness will eventually lower form error values even farther.

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Stamp and Damascene Process for Micro-Structure Reproduction on Glass Substrate

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1 Introduction

The circuit-like pattern of micro-structures is required on a glass substrate. The pattern is designed, for instance, on the optical circuit of a light processing unit, on the electrical circuit of a CSP(Chip Size Package) board or on the fluidic circuit of a μ-TAS (Micro Total Analysis Systems).

The circuit-like pattern, which has thin lines of 10-200 μm in width, is now fabricated on the glass substrate using photo-lithography masking and HF wet-etching [1] or SF_6 dry-etching [2]. But the reduction of the manufacturing cost demands an inexpensive reproduction process besides lithography and etching.

The authors introduce an alternative, mechanical reproduction process:

1) to fabricate a convex micro-ridge circuit-like pattern on a ceramic mold
2) to stamp the pattern of the ceramic mold on a glass substrate
3) to damascene a metal or a functional material in the stamped concave grooves

Glass stamp process for optical lens has been developed much, but has been presented a few [3]. As the glass is forged at 500-700 ℃, a mold should be made of a heat resisting material such as a ceramic. A simple line-and-space pattern, such as a mold of connectors of optical fibers, can be ground on a ceramic substrate with a slitting tool; but a complicated random pattern can not be ground.

2 Experimental method

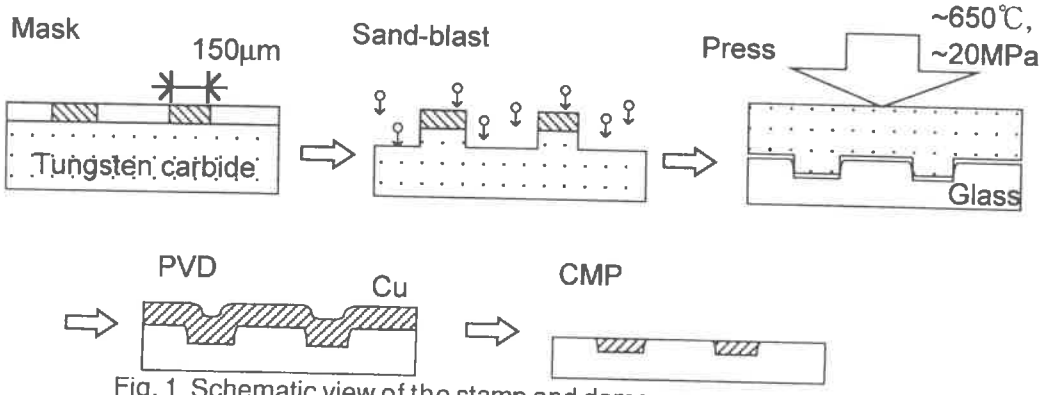

Fig. 1 Schematic view of the stamp and damascene process

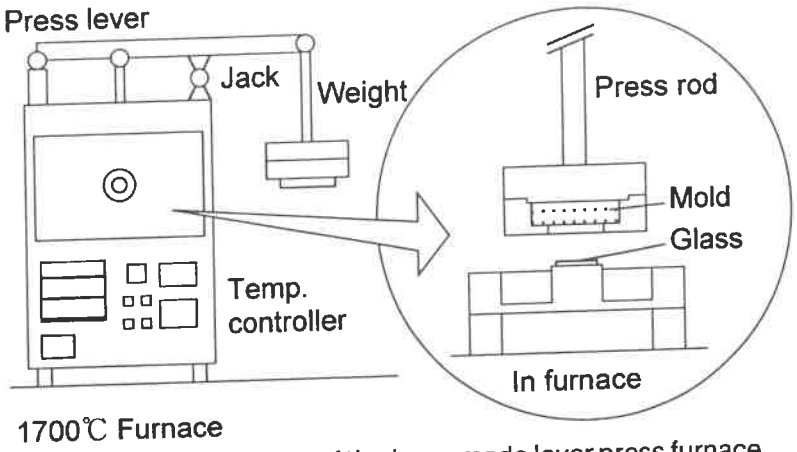

Fig. 2 Schematic view of the homemade lever press furnace

Fig. 1 shows the schematic view of the stamp and damascene process.

We are fabricating the circuit-like random pattern on a tungsten carbide substrate. At first, we draw a pattern of 150 μm wide lines and ϕ200 μm diameter dots on a 30 μm thick polypropylene mask sheet using an FHG-YAG laser, secondly sand-blast the surface with a ϕ2 μm SiC, and eventually dig 1-2 μm deep grooves with removal rate of about 0.1 μm/min.

We are also drawing a dot pattern for biomedical instrument on the same glass substrate. We want to catch one edge of DNA on the aluminum dots and pull the other edge with a ϕ20 nm carbon tool.

Next we press the mold on a glass in a furnace at the following condition: pressure is 20 MPa for 30 minute, temperature is 650 ℃, cooling is in the furnace. Fig. 2 shows the schematic view of the homemade lever press furnace.

Metal damascene process is popular for multi-layered VLSI. The deposited SiO_2, which is almost the same material as a bulk glass, is chemically stable, working as a stop layer in chemical-mechanical polishing(CMP). We are applying the process to the fabrication of the random circuit-like pattern as shown in Fig. 1. We deposit a 2 μm thick copper using sputtering on the glass substrate, which has already been patterned with stamped concave grooves, and polish the copper on the flat surface and remain the copper only on the grooves. The sputtering/polishing condition is as follows: vacuum is 0.6 Pa, sputtering RF power is 100 W, deposit rate is 0.006 μm/min, polish abrasive is a ϕ180-230 nm alumina, polishing solvent is H_2O_2, polishing pad is porous urethane.

3 Results

Fig. 3/Fig. 4 indicates the surface profile of the line/dot pattern of the ceramic mold. The surface has a 1 μm high convex pattern. Fig. 5/Fig. 6 shows the surface profile of the stamped glass along the coincident measuring lines of Fig. 3/Fig. 4. The surface has a 1 μm concave pattern replication is very precise. Fig. 7/Fig. 8 shows the surface profile of the damascened glass. The surface is almost flat, but has a 0.3 μm concave pattern because the copper is overpolished.

Fig. 9/Fig. 10 shows the SEM view of the surface of the mold/the stamped glass. Any line/dot of the pattern is precisely reproduced.

Fig. 11 shows the SEM view of the damascened glass. The copper pattern is exactly the same as the convex pattern shown on Fig. 9.

4 Discussion

We are also fabricating curved triangular grooves of a hologram optical grating on a nickel plated ceramic; we cut the 1μm deep/wide grooves on the mold [2] and plate a 0.1 μm thick platinum on the surface. However, the glass was sticked with the mold. We need the optimum lubricant condition of the platinum.

We could reproduce the 1-2 μm deep pattern, but the press time was too long such as 3 hour. Infrared heating system is necessary for quick heating and cooling. We will be able to shorten the reproduction time to 5 minutes.

We tried a fine pattern which has 30 μm wide line. But the 30 μm wide mask was peeled during sand-blasting. We now try to directly draw the pattern on the mold using the FHG-YAG laser.

5 Conclusion

We fabricated the circuit-like pattern which has 150μm wide lines and ϕ200μm diameter dots with the stamp and damascene process. The prototype fabrication confirmed that the stamp and damascene process worked as designed for micro-structures reproduction. Mechanically, we could replicate the micro circuit-like pattern.

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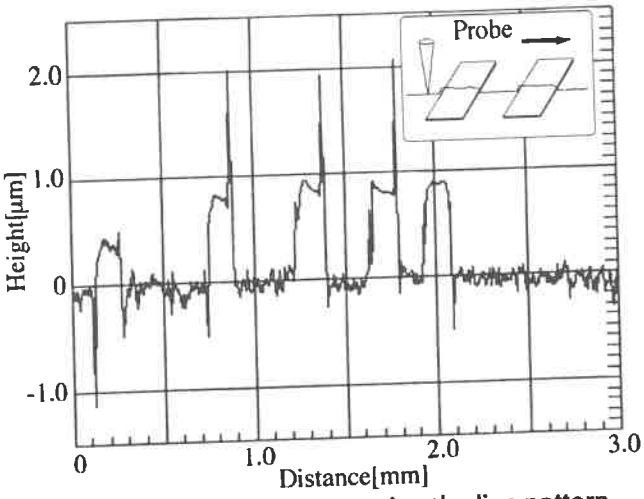
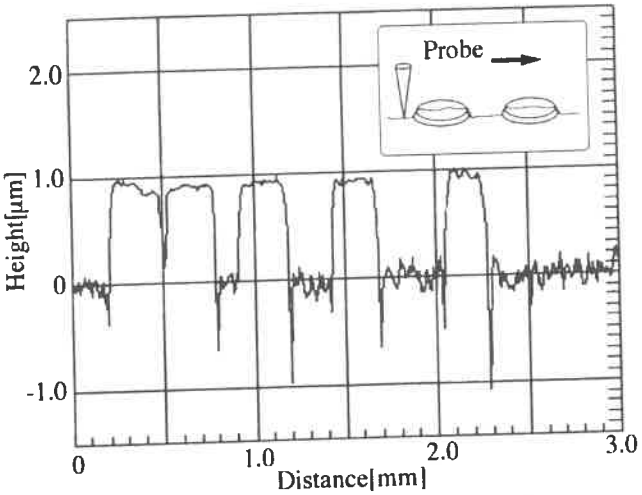


Fig. 3 Surface profile crossing the line pattern of the ceramic mold



F ig. 4 Surface profile crossing the dot pattern of the ceramic mold

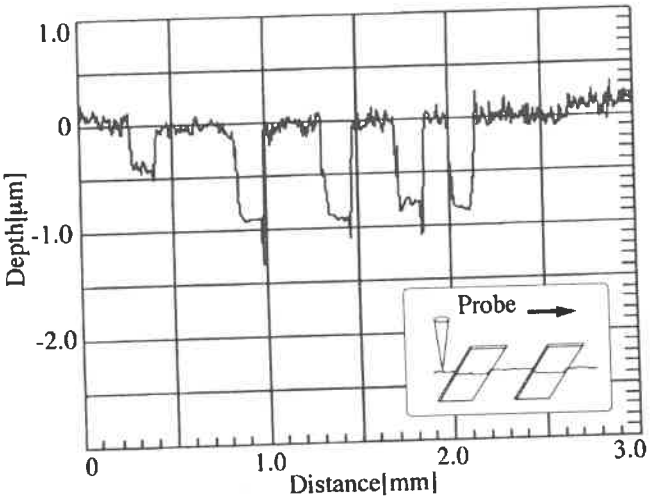


Fig. 5 Surface profile crossing the line pattern of the stamped glass

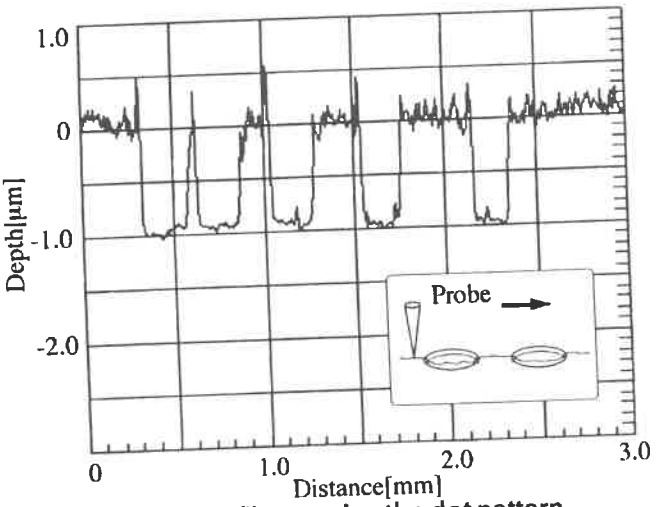


Fig. 6 Surface profile crossing the dot pattern of the stamped glass

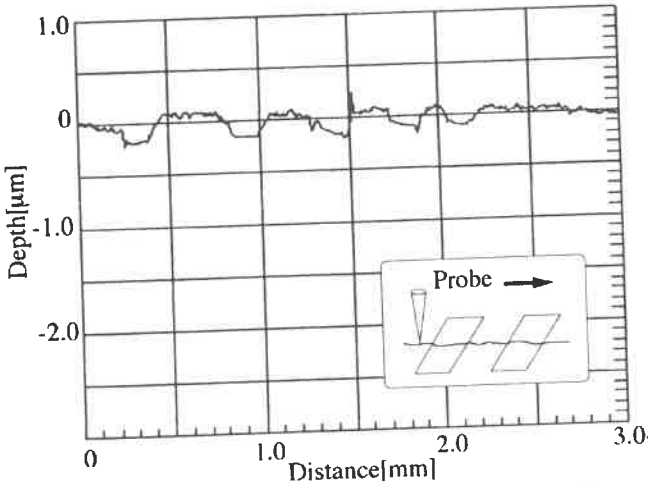


Fig. 7 Surface profile crossing the line pattern of the damascened glass

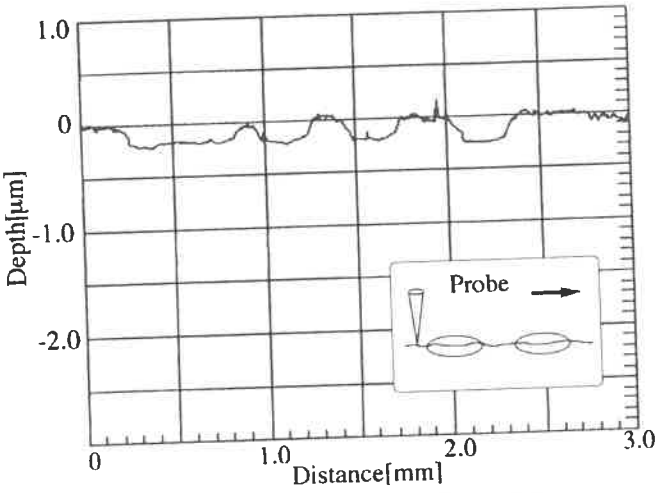


Fig. 8 Surface profile crossing the dot pattern of the damascened glass

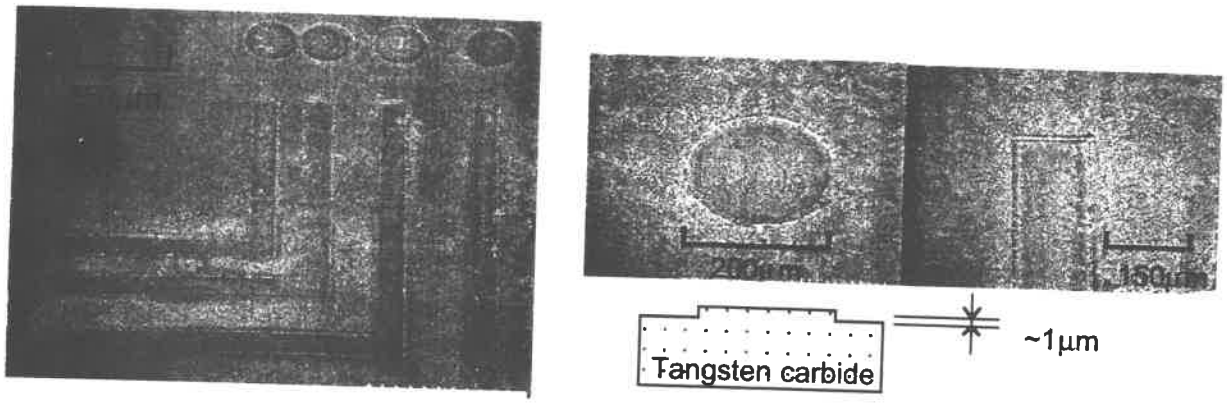


Fig. 9 SEM view of the ceramic mold surface

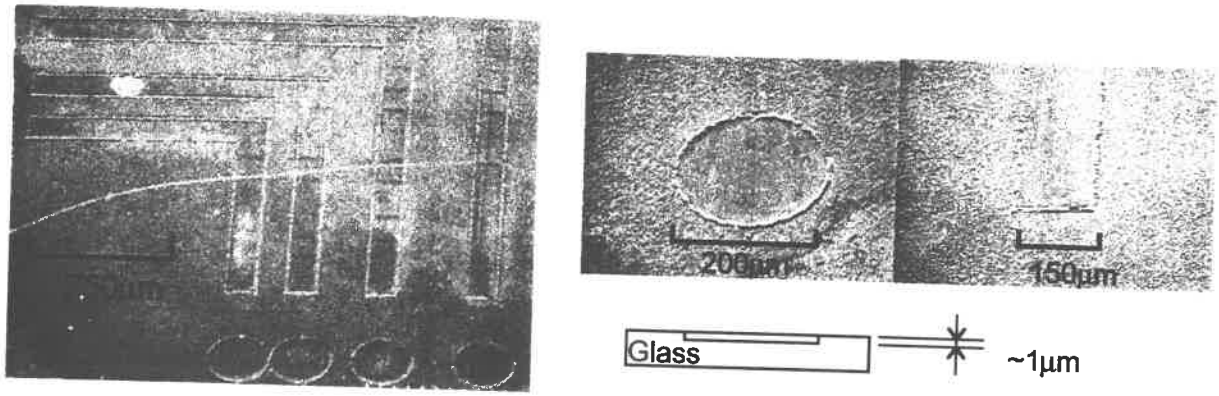


Fig. 10 SEM view of the stamped glass substrate

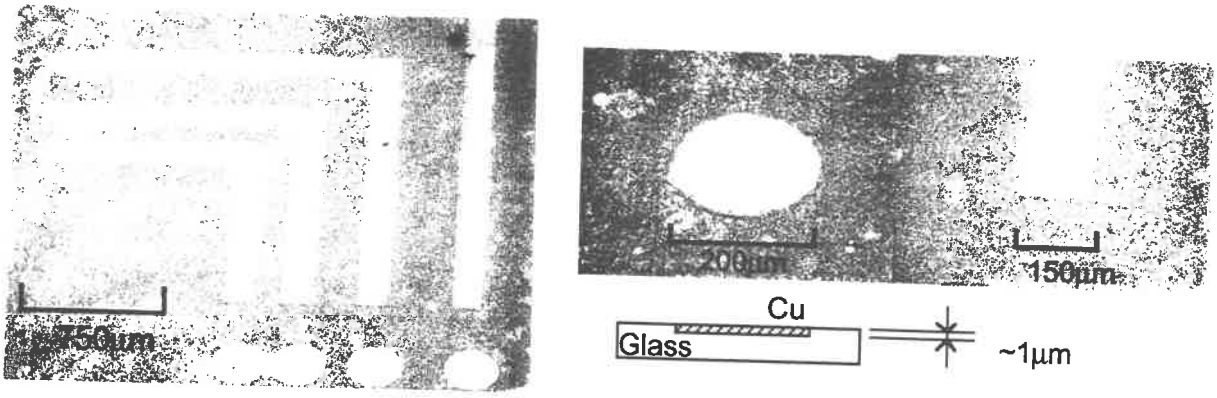


Fig. 11 SEM view of the damascened glass substrate

Focused Ion Beam Machining of Molds

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Almost 30 years of development of focused ion beam (FIB) technology, based on Ga^+ liquid metal ion sources invented in the late 1970's, has resulted in the extremely versatile high resolution computer controlled FIB Micromachining work stations of today. Today's FIB systems can both remove and deposit material with approximately 5 nanometer resolution making them an indispensable the microelectronics industry, for trimming of disk drive read/write heads during manufacturing and for other tasks such as modification of nanoindenter or AFM probes, drilling of micro apertures, etc. FIB combined with appropriate introduction of selected chemicals is utilized both for deposition of materials such as metals (decomposition of organometallics) or insulators (e.g. deposition of SiO_X using TEOS) and for enhanced material removal (e.g. the removal rate of diamond can be enhanced by a factor of 10 through the use of H_2O as the chemically enhancing species). These attributes can be utilized for production and/or modification of micro molds for optics, MEMS devices, and other technologies requiring removal and deposition of material on the nanometer to micron scale.

A FIB workstation consists of a FIB column, a precision stage, introduction system for the chemicals used for materials removal rate enhancement and for material deposition, a vacuum system and a computer control system. FIB columns consist of a Ga^+ liquid metal source (a stable, very bright (100's of mA/cm^3) source of ions originating from a spot of about 2nm in diameter), focusing optics to shape the beam, steering plates to control the position of the beam and a beam blanking system to turn the beam on and off. The object to be micromachined is mounted on a precision stage having sub micrometer positioning resolution and usually equipped for sample tilting and rotation for added versatility. Chemical introduction systems rely on leak valves to control flow of chemicals and needles to direct the chemicals to the proper location. The computer control system controls the FIB column, stage position, and chemical introduction systems. In addition, the computer is used to generate patterns used to micromachine desired structures and to control the Ga^+ ion beam position an blanking. The combination of the above subsystems result in an extremely versatile tool for high precision material removal and deposition.

In order to remove material[1], the computer controlled ion beam is at a chosen point on the sample and allowed to dwell on that point for a predetermined time in order to sputter or machine away a desired amount of material. By stepping the beam in a predetermined pattern and allowing it to dwell as desired, a chosen region of the sample can be micromachined. This is schematically depicted in Figure 1. When no chemicals are introduced during FIB micromachining, material removal results from physical sputtering, analogous to sand blasting a surface but with nanometer precision. Material removal or sputtering rates achievable through physical sputtering alone range from approximately 0.1 to $1\mu m^3$ per second limiting the scope of material removal to a few thousand cubic micrometers. For many materials, use of appropriate chemicals[2] (See Figure 1) can significantly increase the material removal rate by assisting in the

production of volatile species e.g. the removal rate of diamond can be increased by an approximate factor of 10 utilizing H_2O[2]. If a suitable organometallic chemical is introduced, material can be deposited. The rate of material deposition is also limited to the thousands of μm^3. Even though the volume of material removal and deposition are limited, FIB micromachining provides unparalleled versatility and precision for the micromachining, of the high value microfabricated products of modern technology.

An example of practical FIB micromachining[3] of a diamond tool is presented in Figure 2. A nanoindenter employed in the study of material hardness and other properties is depicted both before and after micromachining. Although the diamond indenter tip has a very small end radius prior to FIB micromachining, the shape is not of the desired Berkovitch geometry and the surface of the indenter is very rough (Figure 3A and 3C). The diamond nanoindenter tip was positioned in order to have a 135° angle between the axis of the indenter and the axis of the focused ion beam as shown in the schematic in Figure 3. H_2O was then introduced into the FIB vacuum chamber to enhance the material removal rate and the chosen face of the indenter was then "shaved" at 135°. The indenter was then rotated 120° and the process repeated until all three sides had been micromachined to the proper angle and smoothness. It is clear that the resulting shape and smoothness of the diamond indenter much more closely approximates the desired three sided, 135° Berkovitch geometry while maintaining an end radius of less than 100nm.

FIB micromachining holds much potential for custom fabrication of molds and/or stamps having complex submicron features. Two dimensional maps having focused ion beam dwell time (and thus the amount of material removed) as the third dimension can potentially be used to create arbitrary structures with nanometer precision features. This dwell map technique was utilized to FIB micromachine two test structures into silicon (See Figure 3). For the first structure, a dwell map was created based on the intensity of a sine wave which repeated radially out from center with a repeat distance of 1/16 of the map diameter. The intensity of this sine wave was then exponentially damped based on distance from center. An AFM image of the 16μm diameter structure resulting from the FIB micromachining of the above pattern into Si is presented as a contour plot in Figure 3A along with a cross section plot in Figure 3B. Another test pattern was produced by conversion of a digital image of the NC State University seal into a two dimensional FIB dwell map. The result of the micromachining into Si of this approximately 20μm pattern is presented in Figure 3C. The pattern complexity and micromachining resolution illustrated by these two examples clearly show that complex, high precision micro molds and/or stamps of technological significance can be created. This technique can also be used to correct microscopic defects in precision manufactured structures e.g. defects in diamond turned surfaces. In conclusion, it is very probable that the as yet untapped potential of FIB micromachining to create complex nanometer precision structures will have an increasing technological impact as the size of engineered structures shrink and as the precision required for their manufacture increases.

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2. T.J. Stark, D.P. Griffis, and P.E. Russell, J. Vac. Sci. Technol. B **14**, 3990 (1996).
3. P. E. Russell, T. J. Stark, D. P. Griffis, J. R. Phillips, and K. F. Jarausch, J. Vac. Sci and Technol. B 16(4), p. 2494 (1998)

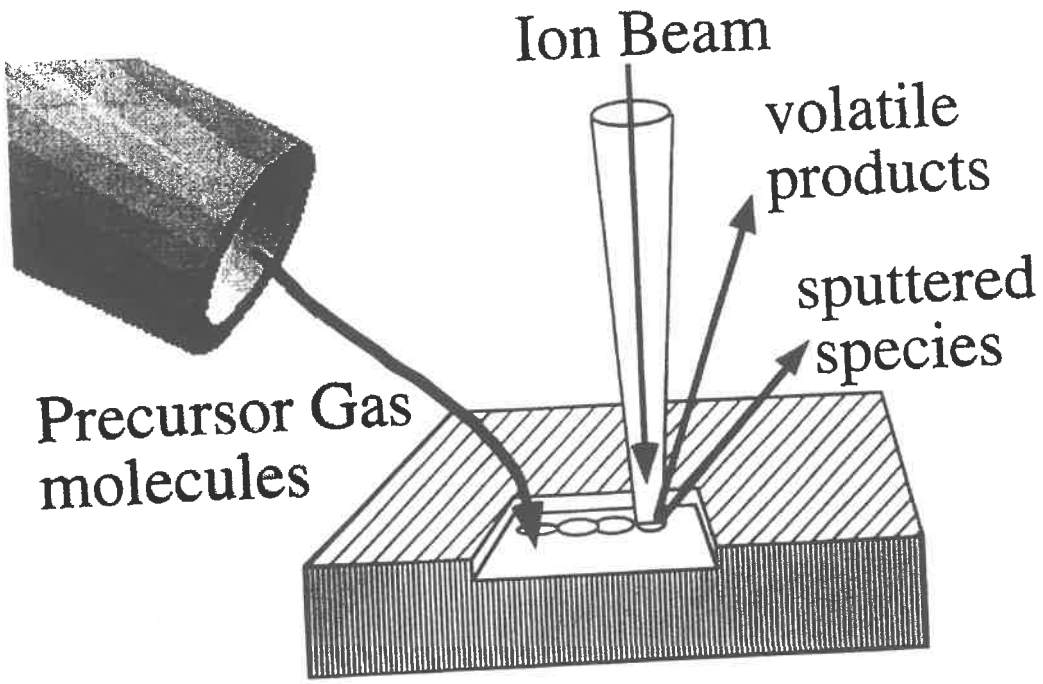

Figure 1: A schematic view of a sample undergoing focused ion beam micromachining.

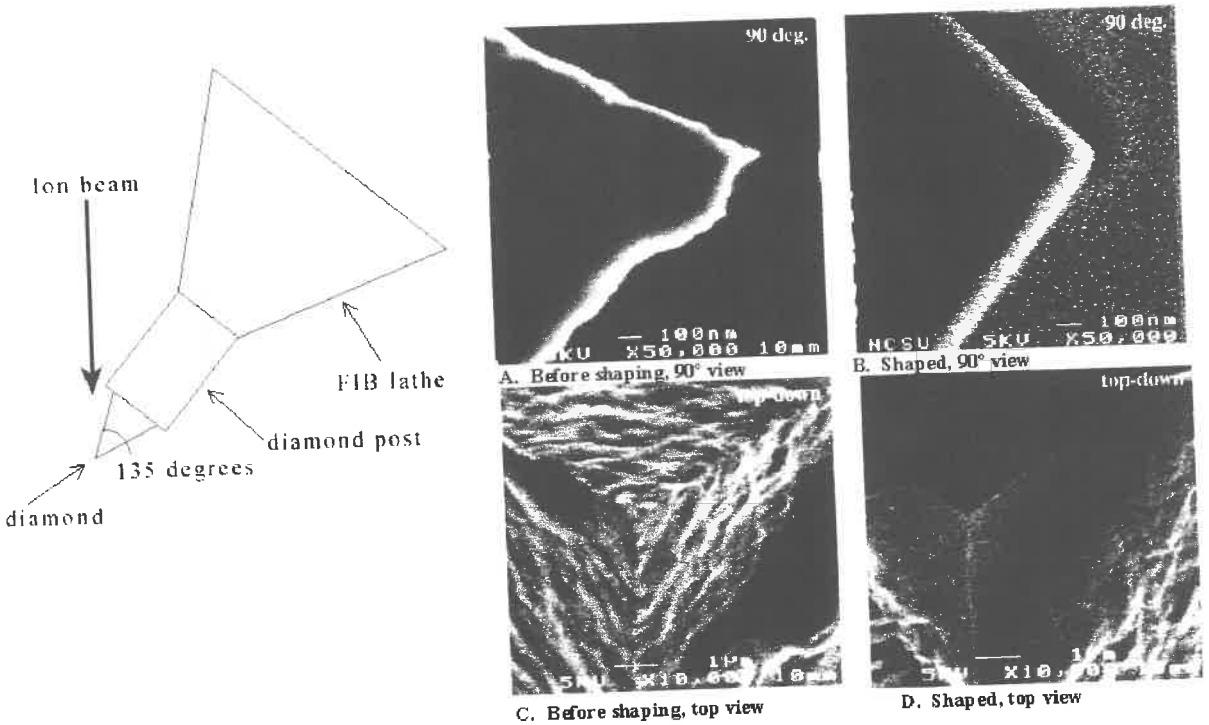

Figure 2: The schematic shows the position of the diamond indenter tip with respect to the ion beam. Scanning electron microscopy (SEM) micrographs) of the diamond indenter as received are presented in A (side veiw) and C (top down view). SEM micrographs of the diamond indenter micromachined into the desired shape are presented in B and D.

Figure 3 A

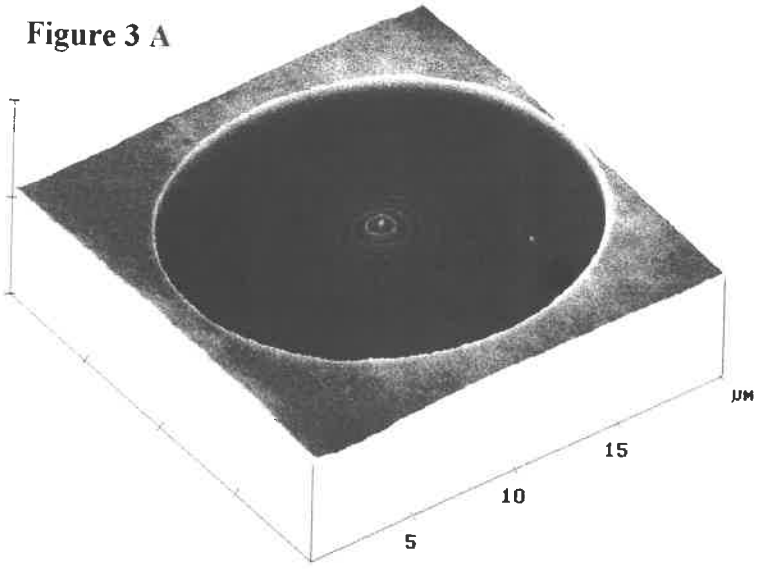

Figure 3 B

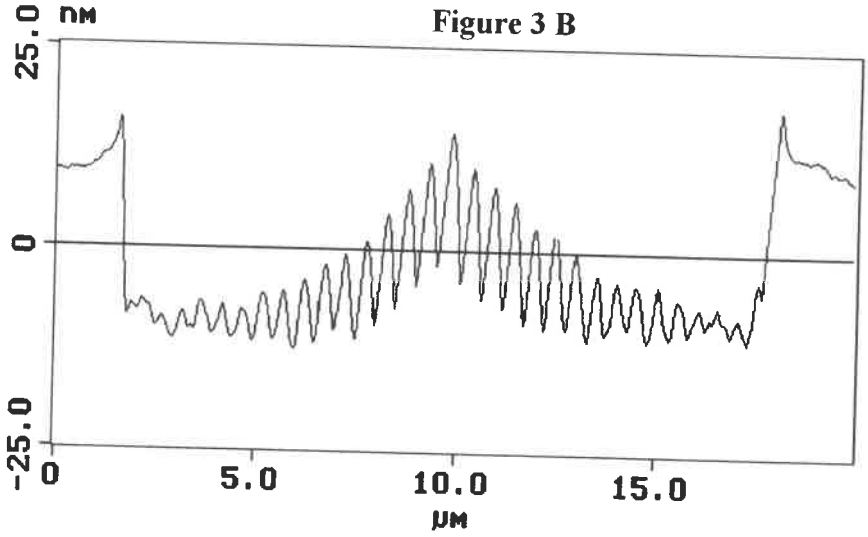

Figure 3 C

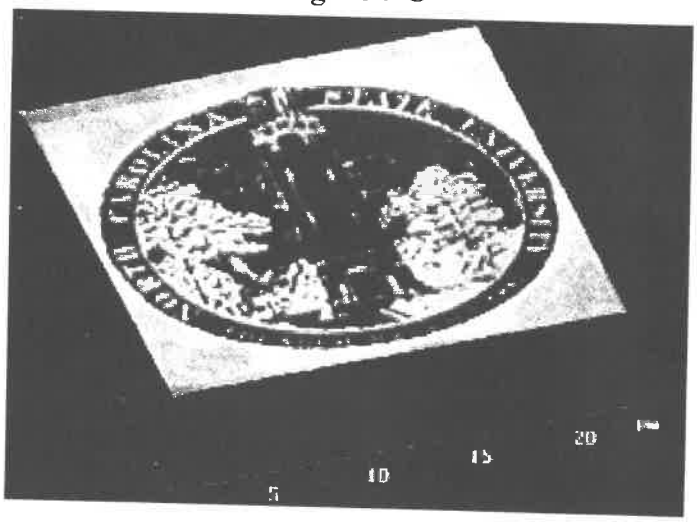

Figure 3: An AFM scan of a FIB micromachined exponentially damped Sine wave pattern (3A); a cross section of 3A (3B) and a micromachined pattern of the NC State seal (3C) illustrating FIB micromachining capability.

REPLICATION TECHNIQUES IN PRECISION MACHINE ARCHITECTURE

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In this case replication refers to the use of epoxy-based polymers with a putty or fluid consistency. When cured against an accurate surface they become finished low friction slideway surfaces, hydrostatic bearing surfaces or surfaces appropriate for mounting precision components such as rolling element bearings or air bearings. By precision machining a master once its accuracy can be replicated into machine structures repeatedly. Replication eliminates many machining or scraping operations, facilitates standardization and reduces cost associated with precision machine erection.

A replication material was used to produce the hydrostatic bearings on the main vertical and horizontal ways of a large Bryant Planetary Grinder. Each slide has four bearing elements that are five to six feet apart. It would be very difficult to machine these bores to the required tolerances. For this reason, replication material was employed to replicate the outside diameter of mandrels that were of correct diameter, straight and aligned parallel with each other. A mandrel is shown prior to insertion in figure A1. The magnetic strips that will form the hydrostatic pressure pockets and return ports are also visible on the table. The magnetic strips are positioned on the mandrel (figure A2). Care is taken to be sure the mandrel does not sag and that it is straight and parallel with the other mandrel. The replication material is then injected around the mandrels as shown in figure A3. The next day the mandrels are removed and the magnetic strip is peeled out of the cured material leaving pockets in a finished hydrostatic bearing (figure A4).

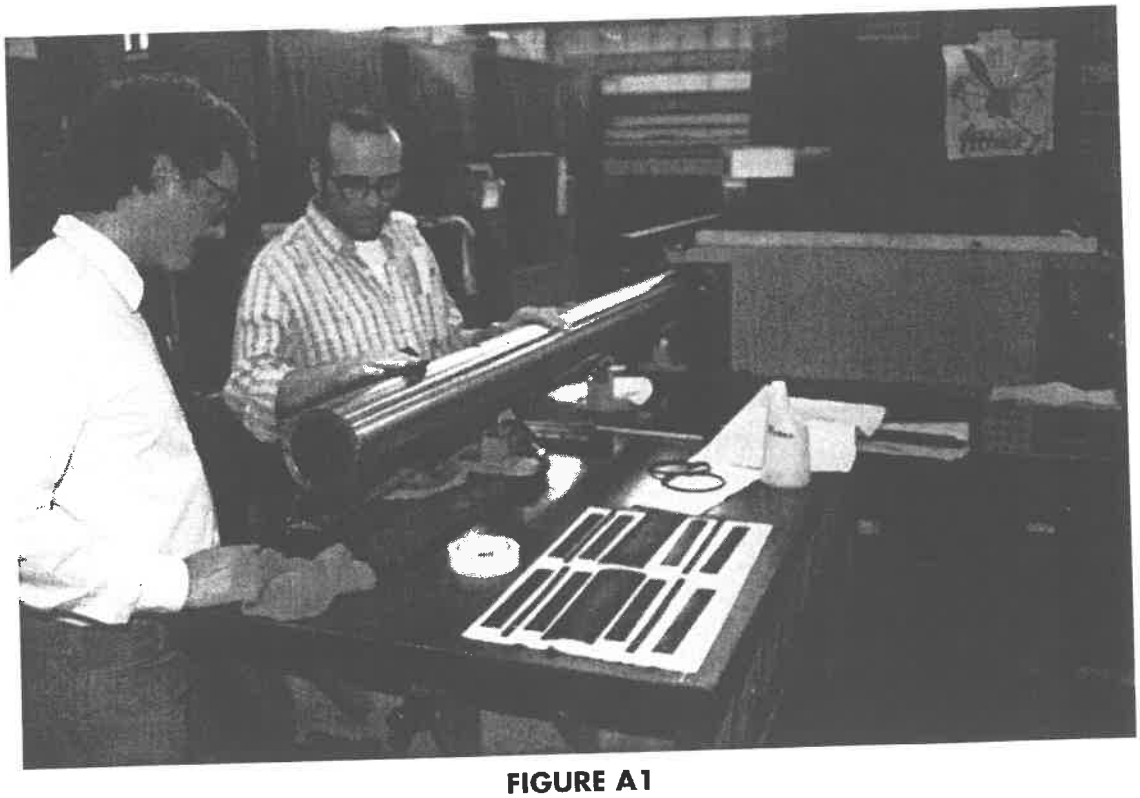

FIGURE A1

FIGURE A2

FIGURE A3

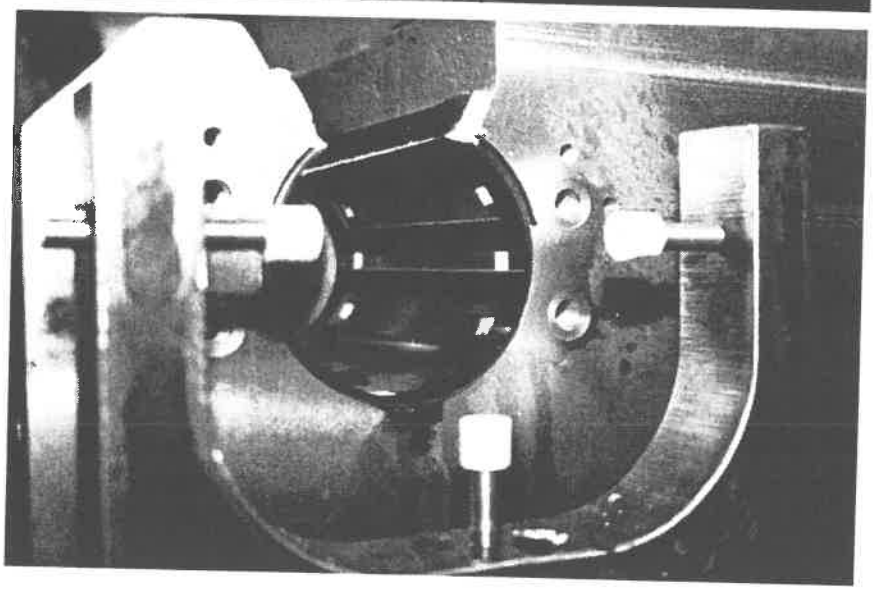

FIGURE A4

When manufacturing large cylindrical bearings a machining error on the side of excessive clearance can result in expensive scrap or rework. When using a replication material this problem of machining to fit is eliminated because the replication material will conform to the molding master. Even if there was a problem with a replicated bearing, the replication material could be readily machined out or removed with hand tools and the bearing remolded. This feature is especially significant if bearing failure should ever occur in service because the bearing could be remolded in the field without recourse to machining. This greatly reduces any potential down time and the cost to repair the bearing.

Low-friction replication materials have been shown to possess long wear life even in adverse conditions such as in a loss of lubrication. These emergency running and non-galling properties reduce the chance of failure should a hydrostatic pressure loss or physical contact occur. Even if catastrophic failure should occur, the replication material being softer and non-abrasive is not likely to damage its mating surface.

These wear properties also make it more practical to consider less hydrostatic clearance or the use of water-based hydrostatic fluids, potentially reducing heat and coolant contamination problems. The use of newer more dimensional stable structural materials (i.e. ceramic, epoxy-granite) and the use of replication materials to cast very accurate hydrostatic bearings also make lower clearance hydrostatic bearings more practical. Less hydrostatic clearance results in greater hydrostatic stiffness and less flow reducing the size of pumps required.

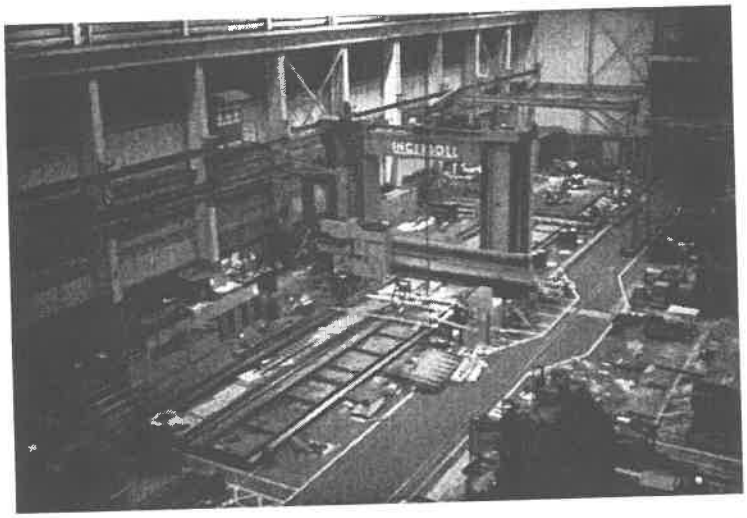

FIGURE B1

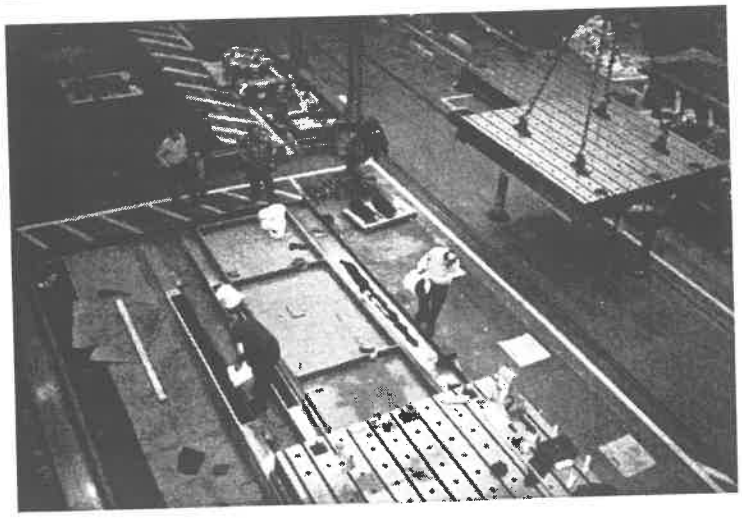

FIGURE B2

A large Ingersoll planer mill built in the early 70's began to experience stick-slip effects in the table motion (Figure B1). The original equipment builder recommended returning the table segments to have the phenolic replaced with Turcite, a teflon based bearing tape. Because the table was in 7 sections and weighed over 200 tons just the shipping would have been expensive. Alternately, we were able to mill off the phenolic wear material in their facility using in-place-machining techniques (Figure B3) and refit the table to the bed ways using Moglice replication material (Figure B2). In order to improve oil distribution under the table two oil groove patterns were employed. A shallow (.010") groove network was molded in (Figure B4 & B5) and a deeper pattern was cut into the bearing with a router. The segments were pre-aligned on precision shims and then set into pools of moldable bearing material (Figure B2). When cured the replication material perfectly conforms to the bed ways and adheres to the table segments while they are in there correct alignment (Figure B6). By using a master height gauge and electronic levels to align each segment, the entire table, 55' long and 26' across, was held to a plus or minus .0015" elevation tolerance.

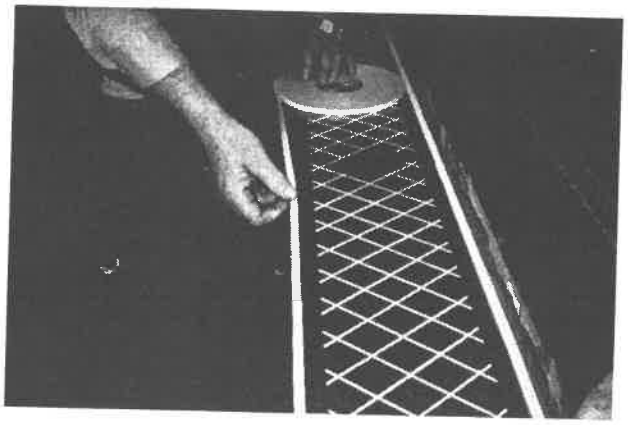

FIGURE B4

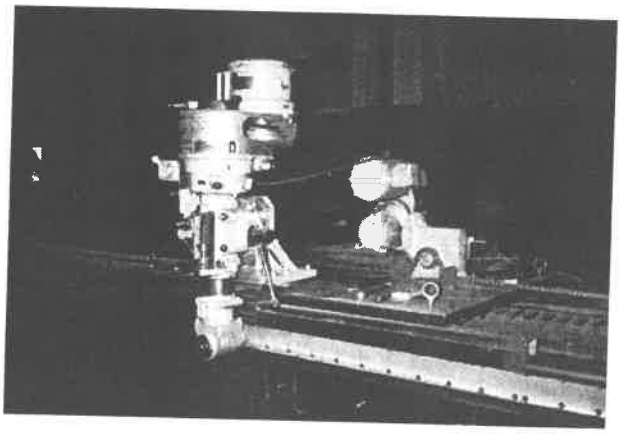

FIGURE B3

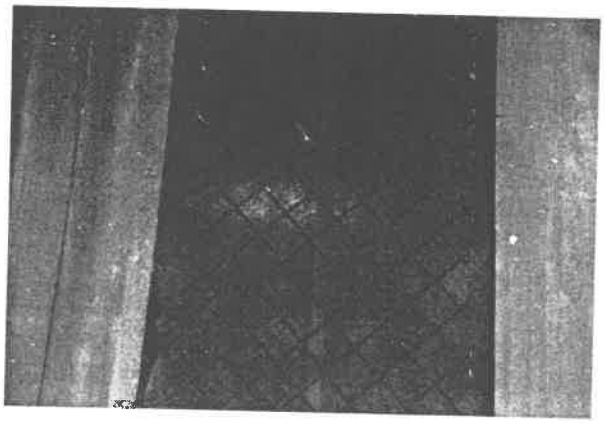

FIGURE B5

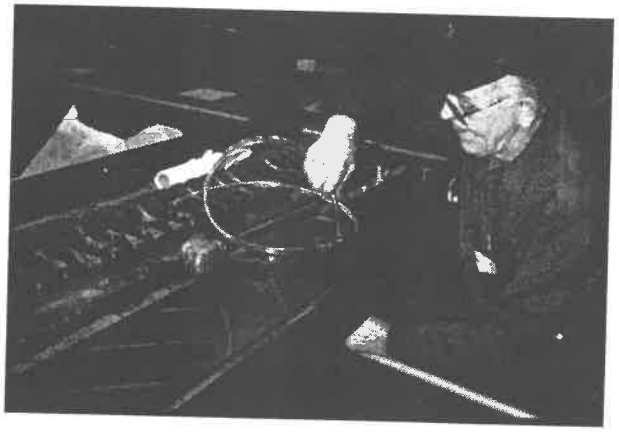

FIGURE B6

Replication was used in a patented "Vacuum Replication Process" to assemble air bearings into a precision stage used for dry diamond machining (Figure C1). The six load carrying air bearings, each 6" x 12", are held perfectly parallel to the guide ways by drawing vacuum to the pressure ports (Figure C2). Replicant is applied to the back of the bearings and the stage is set into its correct alignment over the bearings.

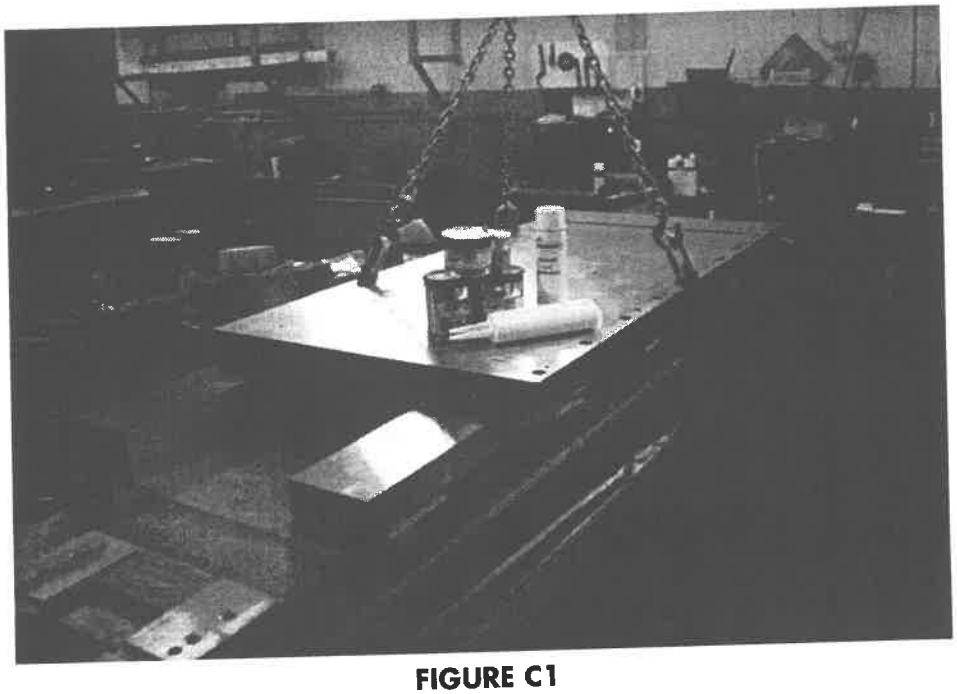

FIGURE C1

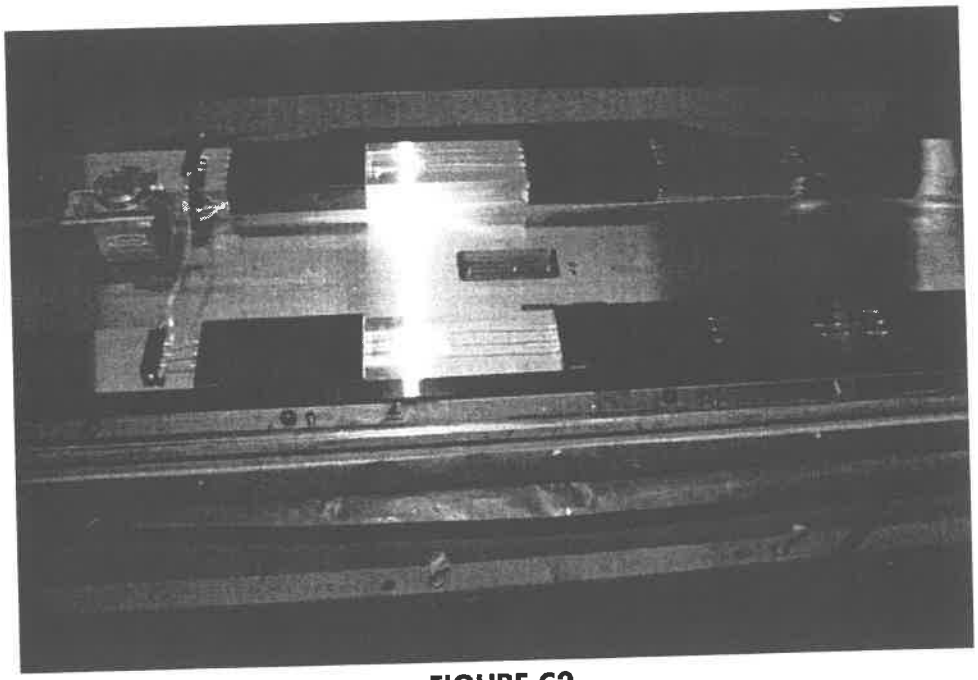

FIGURE C2

Twenty hours later with the replicant cured, the stage is removed with the bearings secured (Figure C3). The opposite line side (no gib used) and both keeper ways are then replicated in the same fashion (Figure C4). It would have been very difficult to attempt to match machine air bearing surfaces on the stage. The vacuum replication process makes air bearings more practical for large machines. Theoretical capacity for this stage would be about 25,000 lb. And it was tested successfully with 10,000 lb.

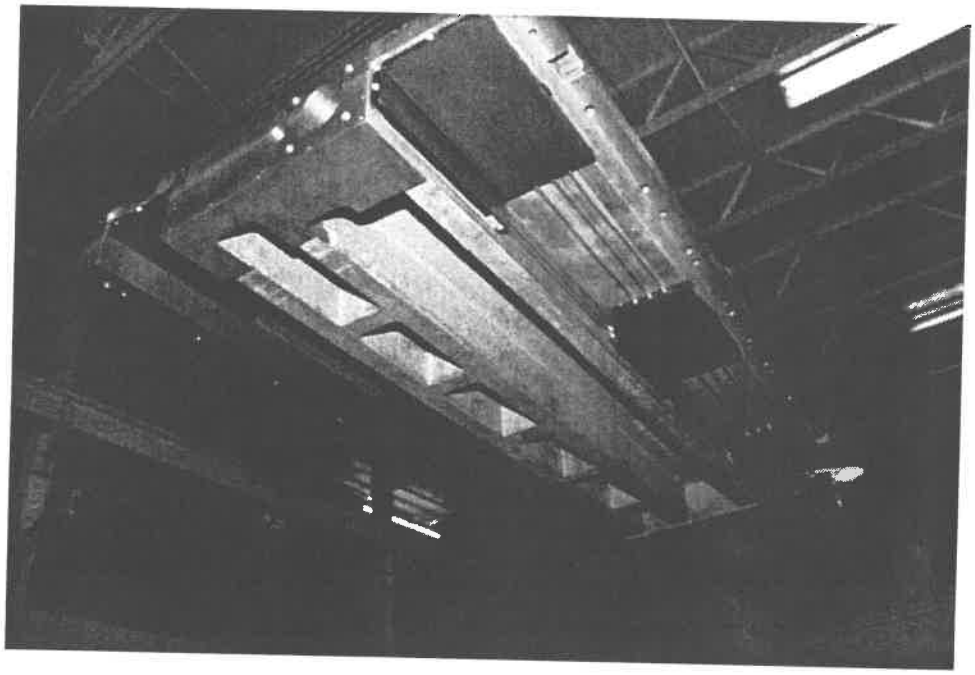

FIGURE C3

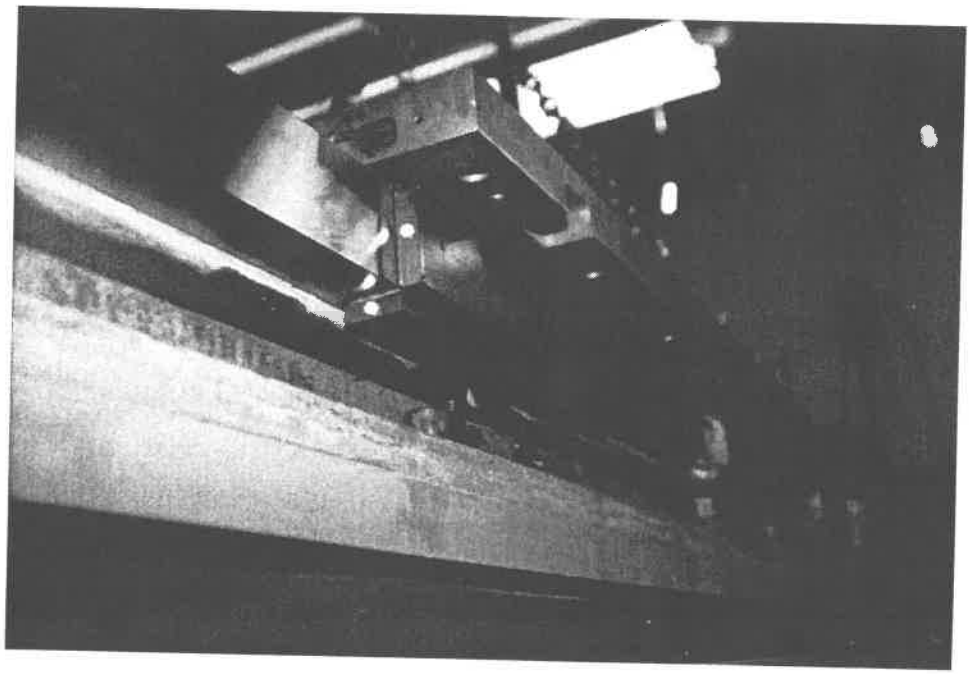

FIGURE C3

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